ORIENTING

D1.4

Critical evaluation of material criticality and product-related circularity approaches

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Acronyms

Acronym	Meaning
AoP	**Area of Protection**
BSI	**British Standards Institute**
CA	**Criticality Assessment**
CE	**Circular Economy**
CEAP	**Circular Economy Action Plan**
CEIA	**Circular Economy Indicators Alliance**
CF	**Characterisation Factor**
CFF	**Circular Footprint Formula**
CIRC(T)	**Name of a Circularity Index**
CRM	**Critical Raw Material**
CTI	**Circular Transition Indicators**
DoW	**Description of Work**
DtT	**Distance-to-Target**
EC-CA	**European Commission’s Criticality Assessment**
EMF	**Ellen MacArthur Foundation**
EU CRM	**European Commission Criticality Raw Material**
ESP	**Economic Resource scarcity Potential**
ESSENZ	**Name of a method to measure resource efficiency of products, processes and services in the context of sustainable development (German for “essence”)**
FRS	**Final Retention in Society**
GLAM	**Global Guidance for Life Cycle Impact Assessment Indicators and Methods (series of projects conducted in the frame of the UNEP/SETAC Life Cycle Initiative)**

Acronym	Meaning
HHI	Herfindahl-Hirschman Index
IRTC	International Round Table on Materials Criticality
ISO	International Organization for Standardization
JRC	Joint Research Centre (of the European Commission)
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LCSA	Life Cycle Sustainability Assessment
LCT	Life Cycle Thinking
LIDS	Life Cycle Design Strategy
MCI	Material Circularity Indicator
ME	Materials Efficiency
NACE	Nomenclature Générale des Activités Économiques dans les Communautés Européennes (French, EU classification system of economic activities)
NEDO	New Energy and Industrial Technology Development Organization
NRC	National Research Council
PACE	Platform for Acceleration of Circular Economy
PCI	Product Circularity Indicator
PEF	Product Environmental Footprint
PGM	Platinum Group Metal
PLCM	Product-Level Circularity Metric
REE	Rare Earth Element
RMI	Raw Materials Initiative
SCI	Sustainable Circular Index
UOR	In-Use Occupation Ratio
VRE	Value-based resource efficiency
WBCSD	World Business Council for Sustainable Development
WGI	World Bank’s Worldwide Governance Indicators

1 Executive summary

The deliverable presents a critical evaluation of existing approaches addressing material criticality and circularity. These topics are dealt with in separate parts.

PART 1: Material criticality

Key ongoing transitions towards a more digital and sustainable future rely extensively on technologies that require critical metals and minerals for their production. These are called “critical raw materials” (CRMs) because of their strategic importance and supply-associated risks (be it for resource availability, geopolitical reasons or other issues). Therefore, several jurisdictions have developed strategies targeting to secure the supply of their economies with these critical raw materials (the EU and USA most notably). As an input and application of such strategies, methods for material criticality assessment are crucial and a substantial number of methods with varying scopes and indicators has been developed over the past 15 years.

For the purpose of this deliverable, CRMs are defined according to European Commission (2017b) as “raw materials of high importance to the economy of the EU and whose supply is associated with high risk”.

As a contribution to the overall objective of the ORIENTING project, i.e., to establish an operational Life Cycle Sustainability Assessment (LCSA) framework for products (including materials), a review and evaluation of methods for criticality assessments in terms of supply risks is carried out in this report. This also includes a closer look at the relationship between critical raw material assessments and assessment methods within other sustainability pillars, especially related to environmental life cycle assessment (LCA), but also to circularity (as 2nd part of this report). The evaluation of prioritised methods and tools for criticality assessment is carried out against a set of criteria developed in Task 1.1 in order to identify the most promising methods for use within a life cycle context and to identify aspects for further methodological development within the ORIENTING project. The criteria could assume values between A and E, with “A” as the best possible/realistic answer and “E” as the worst one. The option of not applicable (“N/A”) was also possible. In the end, the scores were aggregated into an overall score.

A range of important issues have been identified and discussed. These concern the kind of input data needed and compatibility with LCI data (section 4.1), the question to which of the three pillars of sustainable development circularity belongs (4.2), the extent to which subjectivity (e.g. thresholds) is included in criticality assessments (4.3), dynamic aspects (i.e., inter-annual variability and prospective assessments; 4.4), the availability of data of a sufficient quality (4.5) and finally the link between criticality and circularity (4.6).

Seven methods have been selected for evaluation against the T1.1 criteria:

1. National Research Council (NRC) (National Research Council, 2008),
2. European Commission’s Critical Raw Material methodology (here referred to as European Commission’s Criticality Assessment, EC-CA) (European Commission, 2017b, 2020c),
3. Yale methodology (Graedel et al., 2012), including extensions (Graedel, Harper, Nassar, & Reck, 2015; Ioannidou et al., 2017),
4. ESSENZ (Bach et al., 2016b),
5. British Geological Survey (Shaw, 2015),
6. Japan’s Resource Strategy (NEDO) (Hatayama & Tahara, 2015) and
7. GeoPolRisk (Cimprich et al., 2017, 2018; Gemechu et al., 2016).

The evaluation of these methods against the T1.1 criteria (see chapter 5) suggests that all analysed criticality methods have a relatively high overall rating, i.e., between A and B, except for NRC scoring C+. According to the analysis discussed in section 6.2, EC-CA and GeoPolRisk appear as the two most promising approaches to consider in WP2, noting the issue of subjective thresholds. Temporal variability should be accounted for by facilitating regular updates. Making suggestions for prospective analyses appears to be out of the scope of the ORIENTING project.

There can be links between criticality and the three pillars of sustainability (see section 4.2). As long as there is no double-counting issue with the environmental assessment (e.g. based on the PEF methodology (Zampori & Pant, 2019)), criticality can be classified as "non-environmental". As far as the social and economic domains are concerned, the answer is not as clear cut. Indeed market (i.e., economic) and geopolitical (i.e., socio-political) factors contribute to overall supply risks. When following Sonderegger et al. (2020), criticality belongs to the economic pillar because "impaired product functions" and "additional costs of production" are the corresponding endpoints to be assessed. It needs to be emphasised that treating criticality as part of the economic dimension of sustainability will imply changes in the conceptualisation of LCSA as originally proposed by UNEP/SETAC (UNEP/SETAC LCIn, 2011) (further discussed in section 6.3).

PART 2: Product-related circularity

Striving for the political target of a Circular Economy (CE), as exemplified in the European Commission's (EC) Circular Economy Action Plan 2.0 published in 2020, different circularity metrics have been developed that are used in a variety of contexts and at different levels. CE seeks to eliminate the concept of waste, that exists in the current linear economy, and minimise the dependence on virgin materials. At a macro level, CE is fundamental to achieve sustainable development, with a systemic change needed at an economic, organisational and product level. In the context of the ORIENTING project, focused on the assessment of products, CE and circularity are intended to promote the extended and/or cyclical use of products, as well as their parts and materials. However, a universally agreed definition of Circular Economy is lacking at present - which might be remedied through a new standard being produced within the ISO Technical Committee 323.

As said, the focus of ORIENTING is on the circularity of products. In companies, ecodesign is used to "design in" strategies related to circularity that include materials reduction, durability, disassembly, refurbishment, recycling (see for example IEC 62430:2019). The concept of "material efficiency" is often used to refer to strategies aimed at reducing material input and generation of waste associated from products. CE strategies have the goal to promote the availability of more sustainable products on the market, which ultimately requires to assess their environmental, economic and social impacts. In this respect, ORIENTING will embed CE aspects in the overall analysis of environmental, social and economic impacts (LCA, sLCA and LCC). The work completed within ORIENTING may also make a useful contribution to the new Sustainable Product Initiative (SPI) of the European Commission.

Against this background, Part 2 of this deliverable has the following objectives: identifying relevant approaches, concepts, methods and indicators related to circularity of products to be integrated into ORIENTING's LCSA framework; conducting a critical evaluation of a selection of the most promising indicators for use in LCSA; providing recommendations for methodological developments that feed into WP2 of the ORIENTING project. These objectives are achieved through a combination of systematic literature review, expert interviews and the analysis of prioritized methods and tools based on pre-defined evaluation criteria.

Considering the very prolific production of CE-related literature, the starting point was to identify the literature cited in or citing at least one of two recent review papers of high quality, i.e., Moraga et al. (2019) and Saidani et al. (2019). Further criteria were applied to reduce the number of approaches to analyse to a manageable number, notably product-level indicators which are not specific to one product and cover more than one CE strategy. Nine methods were identified that were analysed against the T1.1 criteria, as presented in section 8.3:

1. Product-Level Circularity Metric (PLCM, C-metric) (Linder et al., 2017, 2020),
2. Material Circularity Indicator (MCI) (EMF & Granta, 2019),
3. Longevity indicator (Franklin-Johnson et al., 2016),
4. Circular Footprint Formula (CFF) (Zampori & Pant, 2019),
5. Product Circularity Indicator (PCI) (Bracquené et al., 2020),
6. Circularity index Circ(T) (Pauliuk et al., 2017),
7. Value-based resource efficiency (VRE) method (Di Maio et al., 2017),
8. Sustainable Circular Index (SCI) (Azevedo et al., 2017),
9. In-use occupation ratio (UOR) and final retention in society (FRS) (Moraga et al., (2021).

The T1.1 criteria could assume values between A and E, with "A" as the best possible/realistic answer and "E" as the worst one. The option of not applicable ("N/A") was also possible. In the end, the scores were aggregated into an overall score.

In parallel, interviews with 6 experts from European Environmental Agency (EEA), World Business Council for Sustainable Development (WBCSD) and the convenor of WG3 of ISO TC 323 have been conducted to identify current trends. The interviews suggest that three product-related circularity tools (two from Ellen MacArthur Foundation (EMF) and one from the WBCSD are mostly used by companies. There are indications that the EMF tools seem to be used by companies in the EMF network and the WBCSD tool is perhaps used more widely; although the precise usage is not in the public domain. All of them include a series of indicators and metrics, noting that the tools Circulytics by EMF and CTI2.0 by the WBCSD focus on companies, not products.

Based on the considerations about functional units (see section 9.4), life cycle stages (7.2) and indicators (10), the ORIENTING LCSA framework could address the different CE strategies in the following way:

- **Through adapting the functional unit and proper definition of the reference flow**, taking account of lifetime extensions of products through some CE strategies (e.g. through repair and refurbishment). For other CE strategies, other adjustments or approaches are needed (see next points).
- Distinguishing **life cycle stages** according to relevant steps in a CE: in order to account for CE efforts made along the life cycle of a product and also considering potential social impacts during these stages, treating the product development/design stage and a stage comprising of maintenance, repair and refurbishment of the product separately is suggested rather than "hiding" them in the production or use stages respectively.
- Introducing **dedicated CE indicators**: as suggested by some authors (Helander et al., 2019; Pauliuk, 2018), a set of indicators/metrics (in addition to environmental, social and economic indicators) could be considered to address measures for different products and materials at different life cycle stages.

While the adaptation of the functional unit (including the reference flow) to explicitly specify the lifetime of a product and distinguishing further life cycle stages of relevance for CE measures is straightforward, establishing a balanced list of dedicated indicators is more challenging.

The evaluation of selected circularity methods against the T1.1 criteria (chapter 10) suggests that they all score relatively high overall (i.e., between A and B). As discussed in section 11.2.2, the evaluation is somewhat inconclusive as to which CE method to prioritise for further analysis in WP2. When looking at the overall score and at the compatibility with LCSA, MCI, PCI, PLCM, the Longevity indicator, and UOR/FRS should deserve further consideration. Given its endorsement by the European Commission in the context of the "Product Environmental Footprint", the CFF is expected to be used as part of the environmental LCA. Using constituents of the CFF to establish stand-alone CE indicators could be explored. From an operational point of view, Circ(T) and VRE can be excluded. While CE measures taken in the product system could also simply be described, evaluating CE measures in environmental, social and economic terms (or "absolute terms") needs to be the measuring rod in the end.

In terms of integration, there are two somewhat opposed arguments. First, CE measures are means not ends which calls for a treatment that is not on a par with the three pillars of sustainability. Second, in order to identify trade-offs with the latter, the CE indicator results need to be presented alongside with the sustainability indicators. Either way, an integration with any of the three dimensions environment, economic, social does not appear an option. In the end, the LCSA integration tool should allow sufficient flexibility to be fit for purpose to wide range of stakeholders having varying perspectives, needs and expectations.

PART 1: Material criticality

2 Introduction

The beginning of the 21st century is marked by the fourth industrial revolution, which according to the World Economic Forum could be a great opportunity for a sustainable technological transformation. Notwithstanding, such a technology-driven development implies a large and increasing demand for natural resources, including several metals and mineral resources (European Commission, 2020c; IEA, 2021).

The concerns about the short- to long-term reliability and availability of supplies of natural resources raised from the second half of the 20th century (National Research Council, 2008), especially around those resources that are geographically constrained (i.e., geologically concentrated in only a few countries). Since then, besides the digitalization occurring in developed countries such as the EU27, USA and Japan, energy and mineral commodity prices have been rising due to the large demand growth in countries of emerging economies such as those of BRICS (Brazil, Russia, India, China, South Africa) and other countries (European Commission, 2020c). The importance of securing the supply of these resources became part of national discussions (National Research Council, 2008). Economies with high import dependency for materials (e.g. EU) identified a potential risk of supply disruption of those raw materials that are important to sustain contemporary lifestyles and the prosperity of national and regional sectors, while transitioning towards sustainability. These materials are referred to as Critical Raw Materials (CRMs) in the EU, but other names are also used.

Different materials are evaluated in terms of their criticality. Most studies or methodologies address minerals and metals only (Berger et al., 2020; Graedel, Harper, Nassar, & Reck, 2015; Hatayama & Tahara, 2015; Hayes & McCullough, 2018; IEA, 2021; Mudd et al., 2018; National Research Council, 2008; Sonderegger et al., 2020; Terlouw et al., 2019), while a few others assess biotic materials criticality only (Bach et al., 2017). Other methods further extended the assessment to include several types of materials, such as minerals and biotic materials (Deloitte Sustainability et al., 2017; European Commission, 2020c). Among all, indium, gallium, cobalt, lithium, nickel, tellurium, copper, the Platinum Group Metals (PGMs) and the Rare Earth Elements (REEs) were the materials that were most often assessed (Schrijvers et al., 2020). Sonderegger et al. (2015) also proposed an adaptation of the Graedel et al. (2012) Criticality Assessment (CA) to include water criticality as a limiting factor to economic activities around the world. However, the authors note that the methodology can overestimate water availability while water quality is not accounted for either.

CRMs in general are especially relevant in the development of eco-efficient technologies and other emerging technologies. Few examples of markets where CRMs are crucial include e-mobility, batteries, renewable energies, pharmaceuticals, aerospace, defence and digital applications (Bobba et al., 2020). The key role of these technologies in the development towards a more sustainable future, endorsed by the goals from the Paris agreement and other EU initiatives such as the Green Deal, implies that the continued evaluation and monitoring of both supply risks and environmental impacts is of great importance (Wentker et al., 2019). Hence, the development of analytical tools and CA methods to assess the risks of supply disruption of CRMs is needed (Gemechu et al., 2017).

The analysis of CRMs can be conducted at different levels: from a specific product or technology, company or sector, to country or region. CA can also cover different time horizons from short term (e.g. a few years) to long term (a few decades) scopes (European Commission, 2020c). However, there is no generic approach or international standardization for CA.

The first publicly reported list of CRMs from a structured CA at a macro level was issued by the US National Research Council in 2008 (National Research Council, 2008), as a response to the constraints of minerals observed on the US market. The report defined the criticality of minerals as a function of two variables: the importance of uses and availability (Graedel, Harper, Nassar, & Reck, 2015). In that same year, the EU Raw Materials Initiative (RMI) (European Commission, 2008) was established to tackle the issue of access to raw materials in the EU. It includes a strategy for regularly (every three years) publishing a list of CRMs in the EU (European Commission, 2014b, 2017b, 2020c).

A few years later, in 2011, the European Commission released the first list of critical resources for European economies (European Commission, 2011). In the European policy context, the assessment considered several industrial minerals and metals whose criticality was determined with the help of economic and geopolitical factors: economic importance and supply risk (European Commission, 2017b). Regarding the environmental concerns, the CA method proposed by EC (referred to as EC-CA in the following) only accounted for strict environmental regulation in force in an exporting country that could jeopardise imports into the EU (Klinglmair et al., 2014), thus increasing the supply risk. In this first list, 14 raw materials were classified as critical. In the next update, this number raised to 20 CRMs listed (European Commission, 2014a). Note that in 2015, the OECD published an assessment of the criticality of minerals using two methods, i.e., the EC-CA method and as an alternative to demonstrate physical constraints (i.e., depletion) the production to reserves method (Coulomb et al., 2015). Two other lists were published: European Commission (European Commission, 2017a) – presenting 27 CRMs – and European Commission (2020b) – presenting 30 CRMs. Each version of the CRM list contains small updates of the EC-CA methodology. They aim at improving the characterization of CRMs. However, for sake of monitoring i.e., comparison of results with previous versions, the methodology keeps its core. Besides, the methodology does not yet include the assessment of social impacts (e.g. financing of armed groups, fuel forced labour and other human rights abuses, corruption and money laundering) of the trade of resources, such as recently implemented regulation (signed in 2017, in force from January 2021) on the "conflict minerals" (i.e., tin, tantalum, tungsten and gold) (European Commission, 2016).

Next to US and EU initiatives, countries such as Japan (Hatayama & Tahara, 2015), Australia (Mudd et al., 2018) and China (Andersson, 2020) have also established dedicated task forces to identify CRMs. It is possible to identify in the literature that the two indicators used in EC-CA approach are among the most commonly accepted dimensions of criticality. As economic importance is context- and scope-dependent, the most common discussion is around the factors influencing supply risk. The general driving factors listed by Vogtländer et al. (2019) in the assessment of supply risk were: concentration of resources; political risks; depletion time of resources stocks and reservoir; by-product dependency; concentration of mining and refining companies; sudden growth of demand; recyclability and recycling potential; substitutability; import dependence; and commodity prices. Dewulf et al. (2016) categorized the supply risk factors into four different groups according to their nature: risk factors of physical/technical/geological nature; of economic/strategic/market nature; regulatory/social nature; and of political stability/governance (Figure 1). Due to this diversity of CA approaches, there is an ongoing discussion about criticality methods relationship/harmonization as also noted by the International Round Table on Materials Criticality (IRTC) (Schrijvers et al., 2020).

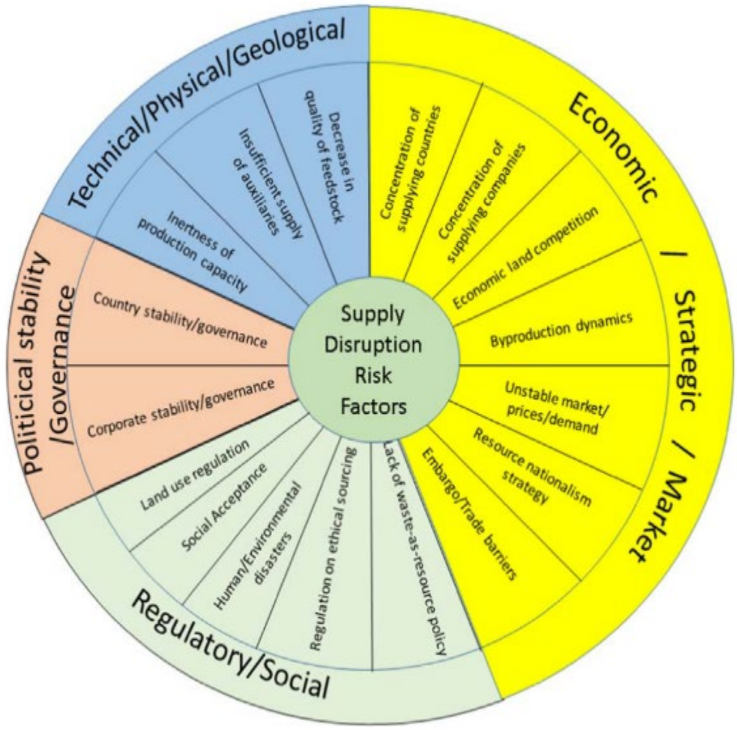

Figure 1. Four categories and factors of supply risk according to Dewulf et al. (2016).

In the bigger picture, there is a link between supply risk of CRM and sustainable development. The EU raw material initiative is directly linked to other policy initiatives like the EU Circular Economy Plan (Santillán-Saldivar et al., 2021). As proposed by the ORIENTING project, an evaluation of CRMs should be considered in the attempt to potentially further develop the product environmental footprint (PEF) into a product sustainability footprint. In PEF (EC-JRC, 2012), life cycle assessment (LCA) is used to support decision-making regarding the impact of products on the environment in general, including the dependency on natural resources. However, the scope of the impact assessment regarding the area of protection “natural resources” is still debated within the LCA community considering that resources use comprises both environmental and economic aspects (UNEP, 2019a).

For clarity, the acronym “LC(S)A” is sometimes used in this document to indicate that both, environmental LCA and LCSA may be concerned.

2.1 Assessing natural resource use in LCA

The notion “natural resources” in LCA encompasses land and sea area, energy sources, water, air, natural biomass (i.e., flora and fauna), minerals, fossil fuels, metallic ores, and nuclear ores (Dewulf et al., 2015). The ORIENTING project was accepted for funding in the call for proposal “Materials life cycle sustainability analysis”. In this context, the concept of “criticality” will thus focus on materials and will be referred to as “material criticality”. As a result, this deliverable will address criticality of minerals, metals and other ores, as well as fossil fuels and natural biomass.

In general, it is well known that one needs to distinguish the use of natural resources and the environmental impacts that their extraction from the environment causes (e.g. Goedkoop, 1995; Heijungs et al., 2010). The latter are already dealt with by impact categories evaluated as part of environmental LCA such as impacts associated to land use, water use and releases from machinery and transport (e.g. respiratory inorganics, photochemical ozone formation, toxicity and ecotoxicity). In an overall LCSA framework, these should, therefore, not be part of the criticality assessment and are thus excluded here.

Although originally proposed for mineral resources in LCA, four general groups of methods can be distinguished assessing the use of natural resources (Sonderegger et al., 2020):

1. depletion methods, which quantify the decrease in resource stocks due to extraction;
2. future efforts methods, which quantify the additional societal efforts required in the future as a result of current extraction;
3. thermodynamic accounting methods, which quantify the exergy lost due to mineral extraction; and
4. supply risk methods, which consider the criticality of mineral resources in terms of supply disruption.

The evaluation of the geophysical availability of materials based on the first category of methods (depletion-based) is yet the most commonly utilized to express resource use in product-level studies in LCA (Di Noi et al., 2020). In PEF, for example, only mineral resource depletion[1] (in kg antimony equivalent according to the CML method) is considered under this Area of Protection (AoP) (Zampori & Pant, 2019). In fact, the Global Guidance on Environmental Life Cycle Impact Assessment Indicators (UNEP, 2019a) recommends that only the so-called inside-out approaches (i.e., approaches that address the impacts of resource use based on the opportunities of future generations to use such resources), such as the resource reserve depletion, are considered in the framework of (environmental) LCA. The outside-in approaches (i.e., the inverse perspective, resource availability for a product system) should be applied to broader life cycle-based approaches, such as LCSA, i.e., not in an environmental LCA. These approaches question the way in which environmental and socioeconomic issues affect the availability of resources for the product system analysed (UNEP, 2019a). As defined by Drielsma et al. (2016), "availability" is also influenced by market demand, stocks, ease of exploration, political stability, which are economic parameters that cannot be disregarded which is beyond the scope of environmental LCA. This is the case of the supply risk methods.

The supply risk of these economically important materials has only come to the attention of national and scientific bodies from the beginning of this century after the first US report on CRM in 2008 (National Research Council, 2008). Since then, the LCA community has engaged in the goal of including supply risk indicators into the framework of LCA as well. A number of recent LCA studies evaluating the impacts of the raw material sector demonstrate the growing need of considering the socio-economic and geopolitical aspects (Berger et al., 2020; Di Noi et al., 2020; Mancini et al., 2015; Sonderegger et al., 2020; Sonnemann et al., 2015; Vadenbo et al., 2014; van Oers & Guinée, 2016). Since these aspects cannot be captured through (environmental) LCA alone, e.g. potential resource accessibility issues related to short-term geopolitical and socio-economic aspects of the supply chain, combining LCA with CA should be considered (Bobba et al., 2020).

The currently well-known supply risk methods in LC(S)A are economic resource scarcity potential (ESP), ESSENZ, and GeoPolRisk. The first approach, ESP, was provided by Schneider et al. (2014). The authors proposed a model for assessing resource competition that considered economic resource scarcity potential (ESP), along with the proposal of an environmental and a social scarcity potential characterization models (Schneider et al., 2014). The ESSENZ method was introduced as an extension and update of the ESP (Bach et al., 2016b). Concurrently, the GeoPolRisk method was developed by Gemechu et al. (2016) to address the raw material supply risk assessment in the framework of LCSA. According to Sonderegger et al. (2020), these

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[1] It needs to be noted that mainly metals are assessed by this method. Further note that water depletion is also an impact category recommended for PEF (Zampori & Pant, 2019). However, as highlighted in the text, only mineral related impact categories are mentioned for discussion.

characterization models of risk to supply disruption of raw materials take into account "the probability of supply disruption resulting from geopolitical and market factors" and "the vulnerability of a user to supply disruptions", similarly to the CA methods developed by the US and EU. However, they are not usually referred to as criticality methods in LCA. This is because there is no consensus on the definition of "material criticality". The following subsection 2.2 will seek to propose a definition for the purpose of ORIENTING's LCSA.

2.2 Definition

In the Cambridge dictionary, criticality refers to "the fact of being extremely important". However, the noun is used to describe different phenomena within specific areas. In the field of mechanics, according to ISO 13372 (ISO, 2012), criticality defines the "index of the severity of an effect combined with the probability of expected frequency of its occurrence". In management, according to ISO 22300 (ISO, 2018), a criticality analysis is the "process designed to systematically identify and evaluate an organization's assets based on the importance of its mission or function, the group of people at risk, or the significance of an undesirable event or disruption on its ability to meet expectations". In the context of material supply-chain analysis, it is usually also used to assign importance to materials of high demand in the supply-chain. However, there is no common agreement on the definition of criticality (Frenzel et al., 2015; Jin et al., 2016; Terlouw et al., 2019).

The concept of material criticality is context dependent. Critical resources are directly associated to economic or political entities (e.g., company, sector, country, or region) and cannot be assessed only from a global perspective (Mancini et al., 2015). Consequently, the definition of the term "critical" and the conditions to the assessment of criticality are necessarily related to the audience perception – in the words of Mancini et al. (2016), "critical to whom?". There is yet no common ground for existing CA methodologies.

Typically, material criticality encompasses different dimensions including supply risks – of a geopolitical and other nature – and vulnerability to supply restriction that in turn is a function of the demand for a given material, its functionality and substitutability or other adaptive capacities of the production system (Dewulf et al., 2016; Knobloch et al., 2018; Sonnemann et al., 2015). The risk to supply disruption is usually interpreted from the occurrence of trade barriers, geopolitical conflicts, limitation of exploration and extraction, and environmental regulations. The vulnerability is usually interpreted from the potential socio-economic effects of this supply disruption (Frenzel et al., 2015; Sonderegger et al., 2020; UNEP, 2019a). As an example, for the British standardization project for material efficiency - CLC/TR 45550 (CEN, 2020), CRMs are the "materials which, according to a defined classification methodology, are economically important, and have a high-risk associated with their supply". For the National Research Council (2008), a mineral is considered critical if there are no or only a few substitutes with the same functional capacity and if it can be proven to have a high restriction of supply shortage due to physical unavailability or high market prices. Similarly, the European Commission defines that CRMs are those "of high importance to the economy of the EU and whose supply is associated with high risk" (European Commission, 2017b).

The study conducted at Yale University (Graedel et al., 2012), however, adds a third dimension to the definition, by also assessing the environmental implications of the processing of the CRMs they look at (i.e., metals). This dimension is then defined in terms of environmental impacts such as toxicity, use of energy and water, and releases to air, water, or land. This is stated to be a first approximation of Life Cycle Thinking (LCT). However, it should be noted that Graedel and colleagues follow a Life Cycle Impact Assessment (LCIA) approach when assessing criticality, i.e., they classify and characterise Life Cycle Inventory (LCI) data with characterisation factors.

In LCA, the characterisation of criticality draws on methodologies suggested at national or supranational levels (e.g. EU). However, also for these methods no single accepted definition exists. There are also authors that associate vulnerability with scarcity, terms of abundance rather than of economic importance (Adibi et al., 2017; Klinglmair et al., 2014; van Oers & Guinée, 2016; Wentker et al., 2019). In this case, the vulnerability is associated to the depletion of natural resources, which is measured as the ratio of extraction to available reserves (Adibi et al., 2017). However, this concept of vulnerability disregards the fact that materials extracted from the ecosphere can be made available to the technosphere as recycled secondary raw materials. Recycling is, for example, one of the strategies promoted by the RMI to reduce risk of supply disruption to economically important commodities in Europe, as well as the promotion of production from local and alternative markets and the substitution of materials for those of similar use and functions. These are mitigation factors that help define criticality in terms of both outside-in burdens and benefits.

For the purpose of this work, a definition of CRM is needed to guide the integration of CA into the operational LCSA developed in the EU-funded ORIENTING project. While the International Round Table on Materials Criticality (IRTC) has not yet provided such a definition (Schrijvers et al., 2020), it is suggested to adopt the definition of CRMs by the European Commission: “CRM are raw materials of high importance to the economy of the EU and whose supply is associated with high risk” (European Commission, 2017b). Thus, the two main parameters to determine criticality are economic importance (EI) and supply risk (SR). In the EU context, the EI indicator provides insights on the potential economic consequences due to inadequate supply of the raw material (Blengini et al., 2017). The importance of a material for the economy is considered in terms of end-use applications and the value added of the corresponding EU manufacturing sectors. The EI also considers the potential use of technologically and economically feasible substitutes for the corresponding applications (European Commission, 2017b). The SR reflects the risk of a disruption based on the concentration of primary supply from exporting countries, accounting for the level of governance performance and trade barriers. *The use of* secondary raw materials (through recycling) and substitution are also accounted as beneficial aspects that reduce supply risks (Blengini et al., 2017) (see further information on the indicators’ formulae in the annex B, section 13.2.2). Since EI is not so often found in the literature as the correspondent to the vulnerability dimension, in this research criticality is primarily assessed in terms of SR, while the EI indicator is considered relevant yet not essential to the definition of critical materials.

3 Method

3.1 Literature review

A review was conducted in order to identify the state-of-art of criticality assessments inside and outside the scope of Life Cycle Sustainability Assessment. As shown in Table 1, a combination of strings related to “Criticality (of materials)” and “methods” was searched in Web of science (WoS) and Google scholar (for literature related and unrelated to LC(S)A) and in Scopus and ScienceDirect (for literature related to LC(S)A). All references published since 2006 were considered at first.

The search of Criticality-LCSA-related literature in Scopus and WoS between December 2020 and mid-April 2021 returned a list of, respectively, 65 and 68 journal articles and reviews. Between those, 44 results were duplicates. In an analysis of abstract, introduction and conclusions, three conditions were used to prioritize the literature for the purposes and scope of ORIENTING: (i) to some extent (conceptual and/or methodological), supply risk (and economic importance[2]) indicators are included in the methods to assess criticality of

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[2] Economic importance only rarely appears explicitly within the LC(S)A+CA literature. Therefore, this was not used as an exclusion criterion.

raw materials and/or resources; (ii) to some extent (conceptual and/or methodological), LCA/LCSA/LCT methods/approaches are included in the study; (iii) LC(S)A concepts and CA are interpreted as complementary. Only review papers and papers presenting methodological proposals and/or advances were filtered. From this screening, 25 documents were selected for further analysis. Besides, four additional documents frequently cited and complementary to the conceptualization of the topic were identified in the reference literature, adding up to 29 documents that based the study on criticality assessments and life cycle thinking.

For literature with no immediate link to LC(S)A, the search on WoS and through Google scholar between mid-February and mid-March 2021 yielded 33 journal articles, reviews and reports. Three more publications could be identified from the review by Schrijvers et al. (2020). So, 36 documents were considered further.

Table 1: Combinations of key words

Method related (not results)	AND Criticality related	(AND) Life-cycle related
“method”	“Criticality” AND “material*”	LCA
OR “Methodolog*”	OR “Critical raw material*”	OR “Life cycle assessment”
OR “Indicator*”	OR “supply risk”	OR “Life cycle analysis”
OR“characterization factor*”[#]		OR LCSA
		OR “Life cycle sustainability assessment”
		OR LCIA
		OR “Life cycle impact assessment”
		<nothing of this column>

[#] This term was only used when also a life-cycle related term from the third column was used.

The literature thus identified (i.e., the 65 documents mentioned above) was further prioritised in three ways. Eleven review articles were excluded because they did not present specific methods that could be analysed. Only those methods were included that have been used (e.g. Graedel et al., 2012) or updated since 2015. Further on, only methods evaluating criticality in terms of supply risk were included for further analysis, noting that criticality can also be analysed in other terms (see Sonderegger et al., 2020). This prioritisation already anticipated the evaluation of two sub-criteria (namely, 3.1 “Traceability of the modelling data and model used” and 5.4 “Degree to which the method/methodology/tool assesses material criticality”) of the criteria list suggested by T1.1, described next. As a result, seven methods have been selected;

1. National Research Council (NRC) (National Research Council, 2008),
2. European Commission’s Critical Raw Material methodology (here referred to as European Commission’s Criticality Assessment, EC-CA) (European Commission, 2017b, 2020c),
3. Yale methodology (Graedel et al., 2012), including extensions (Graedel, Harper, Nassar, & Reck, 2015; Ioannidou et al., 2017),
4. ESSENZ (Bach et al., 2016b),
5. British Geological Survey (Shaw, 2015),
6. Japan’s Resource Strategy (NEDO) (Hatayama & Tahara, 2015) and
7. GeoPolRisk (Cimprich et al., 2017, 2018; Gemechu et al., 2016).

3.2 Evaluation of prioritised methods/tools against criteria provided by T1.1

3.2.1 General description of the T1.1 criteria

The evaluation and comparison of methods, methodologies and/or tools can be based on a set of criteria (in scientific research). In this sense, the criteria to be analysed in ORIENTING project (in WP1) were defined starting from the RACER methodology (**R**obust, **A**ccepted, **C**redible, **E**asy and **R**elevant) (Lutter & Giljum, 2008) and further analysis of a selection of sources found in literature (EC-JRC, 2010, 2011; Eisenmenger et al., 2016; European Commission, 2009; Hauschild et al., 2013; Kujanpää et al., 2017; López et al., 2015; Pelletier et al., 2014; Pizzol et al., 2017; Sala et al., 2018; UNEP, 2019a; Vidal Legaz et al., 2017; Wiedmann et al., 2009). From that, a first set of criteria and sub-criteria was created, exploring the *stakeholder acceptance and credibility*, the *applicability and complexity* of methods/tools, their *transparency*, *scientific robustness*, *completeness* and *compatibility with life cycle approach*.

After a few rounds of internal revision within WP1, where generic and specific issues of the different topics investigated in ORIENTING were tested (environmental, social, economic, criticality, circularity and integration), it became clear that one single set of criteria would not be possible, if relevant interpretation was sought within each topic. Nonetheless, a general set was created, including all items. From that, a few sub-criteria were slightly modified, detailed and/or excluded, depending on the topic they were intended to be assessed. For instance, sub-criterion 4.3 (quality of the modelling data) was made more specific for the environmental topic (i.e., divided into spatial and temporal resolution), while it was excluded for the integration topic, and kept as it is for the other topics (social, economic, criticality and circularity). This final set of criteria (internally referred to as *version 4*) distinguishes the following building blocks:

1. Descriptive summary (with several items, e.g., description of the basic concept)
2. Stakeholder acceptance, credibility and suitability (containing up to eight sub-criteria, depending on the topic);
3. Applicability / complexity (containing up to four sub-criteria, depending on the topic);
4. Transparency (containing up to four sub-criteria, depending on the topic);
5. Scientific robustness (containing up to ten sub-criteria, depending on the topic);
6. Completeness (containing up to five sub-criteria, depending on the topic), and
7. Compatibility with life-cycle approach (containing up to two sub-criteria, depending on the topic)

Each sub-criterion should be evaluated in terms of a score between A and E, with “A” as the best possible/realistic answer and “E” as the worst one. Similarly, to the criteria definition, a common answer (or understanding) was pre-established for each of the sub-criteria scores, which were adapted according to the specifications and needs of each ORIENTING topic. The option of not applicable (“N/A”) was also provided. The simple average of the sub-criteria scores generates the (aggregated) score for each criterion, which also through simple average generates the method’s/tool’s overall score. For this operationalization, the scores of 5 for “A”, 4 for “B”, 3 for “C”, 2 for “D” and 1 for “E” were given. The scores of “N/A” were disregarded. From that, an average result is created (during the evaluation process), that can be a fraction (e.g., 4.43). Thus, the results of the sub-criteria and criteria scores (in numbers) were *converted* back to a letter-coding, while also considering more detailed scores (e.g., A+, A or A-; instead of only “A”), as defined in the Table 2.

The descriptive part, which is not considered for the calculation of the overall scores, is very relevant, nonetheless. In other words, a few relevant characteristics which the ORIENTING team judged not possible to undoubtedly or consistently define as *better* or *worse* (e.g., representation of social scores in qualitative or quantitative way) are still intended to be considered, interpreted and discussed further in the deliverable.

Therefore, not only the overall scores of each method/tool should be considered to define the best methods/tools. It rather should be used with the support of the descriptive section, to identify weaknesses and strengths, and allow a certain categorization of the different methods/tools.

Table 2: Representation of the scores for the criteria or overall scores of each method/tool, in function of the range they fall from the simple average calculations.

Score	A+	A	A-	B+	B	B-	C+	C
Range	[5.0; 4.7[	[4.7; 4.3[	[4.3; 4.0[	[4.0; 3.7[	[3.7; 3.3[	[3.3; 3.0[	[3.0; 2.7[	[2.7; 2.3[
Score	C-	D+	D	D-	E+	E	E-	
Range	[2.3; 2.0[	[2.0; 1.7[	[1.7; 1.3[	[1.3; 1.0[	[1.0; 0.7[	[0.7; 0.3[	[0.3; 0.0[	

The version 4 of the set of criteria was delivered to each task. Each task was allowed to do additional adjustments that are specific for each topic; and this is further discussed in the following subsections (3.2.2, 3.2.3, and 8.3).

3.2.2 Adaptations and interpretations of the T1.1 criteria for the purpose of assessing both, criticality and circular economy methods

Sub-criteria 1.1 “Acceptance by Policy-makers” and 3.1 “Traceability of the modelling data and model used” have been adjusted in the same way for both, criticality and circularity assessments.

The default sub-criterion 1.1 “Acceptance by Policy-makers” only distinguished three scores, assigning multinational bodies a higher relevance than country level. On the one hand, this is misleading for criticality as the effects are the same at both levels. On the other hand, ORIENTING aims at a methodology that is valid for the EU. As a result, established concepts at EU level should be prioritised. Therefore, a five-level score has been suggested and used for both, criticality and circularity (see Table 3).

Table 3: Adjustments of level descriptions for sub-criterion 1.1 “Acceptance by Policy-makers” for both, criticality and circularity

Score for 1.1	Original description proposed by T1.1	Final description as used here
A	Yes, the method/methodology/tool is endorsed by one or more multinational bodies (e.g., EU)	Yes, the method/methodology/tool is endorsed by the EU
B	-	Yes, the method/methodology/tool is endorsed by the one or more multinational bodies other than the EU
C	Yes, the method/methodology/tool is endorsed by one or several governmental bodies (e.g., Germany)	Yes, the method/methodology/tool is endorsed by one or several governmental bodies of an EU member country
D	-	Yes, the method/methodology/tool is endorsed by one or several governmental bodies of a country that is not an EU member
E	No, the method/methodology/tool is not accepted by any governmental bodies or other relevant public organization	(same as original proposal)

For the sub-criterion 1.5 “Credibility among stakeholders”, reference to “transparency” which is evaluated as part of criterion #3 has been dropped as shown in Table 4.

Table 4: Adjustments of level descriptions for sub-criterion 1.5 “Credibility among stakeholders” for both, criticality and circularity

Score for 1.5	Original description proposed by T1.1	Final description as used here
A	Yes, the method/methodology/tool is transparent and can be easily understood and reproduced by non-experts in the field	Yes, the method/methodology/tool can easily be understood and reproduced by non-experts in the field
B	Yes, the method/methodology/tool is transparent and can be easily understood and reproduced by those with basic knowledge in the field	Yes, the method/methodology/tool can easily be understood and reproduced by those with basic knowledge in the field
C	Yes, the method/methodology/tool is transparent and can be understood and reproduced by researchers and analyst with moderate knowledge in the field	Yes, the method/methodology/tool can be understood and reproduced by researchers and analyst with moderate knowledge in the field
D	Yes, the method/methodology/tool is transparent but can be only understood and reproduced by specialists	Yes, the method/methodology/tool can only be understood and reproduced by specialists
E	No, the method/methodology/tool is NOT transparent, nor easily understood	No, the method/methodology/tool is not easily understood

For the sub-criterion 3.1 “Traceability of the modelling data and model used”, five levels are distinguished as shown in Table 5.

Table 5: Adjustments of level descriptions for sub-criterion 3.1 “Traceability of the modelling data and model used” for both, criticality and circularity

Score for 3.1	Original description proposed by T1.1	Final description as used here
A	Full methodological specifications are continuously available and regularly updated	(same as original proposal)
B	Full methodological specifications are continuously available but not updated	(same as original proposal)
C	Few methodological specifications are continuously available and regularly updated	Methodological specifications are continuously available and regularly updated, but incomplete
D	Few methodological specifications are available but not updated	Methodological specifications are available but incomplete and not regularly updated
E	No methodological specifications are available	(same as original proposal)

The levels vary in terms of completeness of documentation (full vs. few) and the degree of up-to-dateness. Given that the overall criterion #3 is on “Transparency”, it was agreed within T1.5 that a full documentation was more important than up-to-dateness. So, the methods should rank A or B, if the documentation was complete, and C or D, if it was not. To decide whether or not a method’s documentation is up-to-date, a threshold was set at 2016: the higher score (A or C) should apply, if a method was first published or updated in that year or after, and the lower (B or D), if the latest documentation was published before 2016.

As regards sub-criterion 4.2 "State-of-the-art" the meaning of the score for B was changed from "*The method/methodology/tool is continuously updated. However, the lack of standardization makes it difficult to establish state-of-art best practice.*" To "*The method/methodology/tool has been updated in the last 10 years and contains robust timeless knowledge*". This change addressed the inconsistency that when a method scores A on this sub-criterion (i.e., "*The method/methodology/tool reflects the up-to-date knowledge on the topic*") then we need to be able to define a "state-of-the-art best practice". However, if there are methods that assess the same topic and are ranked B, the statement about "lack of standardization" means that such a "state-of-the-art best practice" does not exist. However, the topic is the same in both cases. By drawing on the meaning of the score for C (in which only "atemporal" was replaced by "timeless"), the above-mentioned text is retained.

3.2.3 Adaptations and interpretations of the T1.1 criteria for the purpose of assessing criticality methods

For the purpose of assessing criticality methods, the list of criteria from T1.1 has been adjusted in several ways, including regarding the way in which some sub-criteria have been interpreted to be evaluated.

Because criticality is a phenomenon typically evaluated at national if not supranational level and in view of the context of the ORIENTING project, the sub-criterion 5.2 "Ability to be applied to site specific contexts“ was changed in terms of name and the associated levels. The name used for assessing criticality methods is "Ability to be applied to EU context". While trying to answer the question "Is the method/methodology/tool applicable to the EU?" the levels as shown in Table 6can be selected.

Table 6: Adjustments of level descriptions for sub-criterion 5.2 "Ability to be applied to site specific contexts" specifically for criticality

Score for 5.2	Original description proposed by T1.1	Final description as used here
A	Yes, the method/methodology/tool can be applied to site-specific contexts	Yes, the method/methodology/tool can be applied to the EU without modification
B	-	-
C	Yes, the method/methodology/tool can be applied to site-specific contexts if site specific information is made available (have to be collected)	Yes, the method/methodology/tool can be applied to the EU with modification
D	-	-
E	No, the method/methodology/tool includes generic models only	No, the method/methodology/tool cannot be modified such that it can be applied to the EU

Given that some sort of national or supranational scale needs to be evaluated for criticality, already captured by the new sub-criterion 5.2, the sub-criterion 5.3 "Ability to be applied in unspecific contexts (generalization)" has been abandoned.

The way in which certain criteria shall be interpreted has been agreed as follows:

2.2 "Data availability and accessibility" as part of criterion 2 "Applicability / Complexity": There was confusion whether data is meant that one needs to have as a user of the method or data that is needed to derive characterisation factors or other parameters needed by the method that are independent of a given study's "LCI". It was agreed that the main question is: How easily can one get data? For instance, is the data normally reported by a company? Is it available from the bill of materials of a process? Or does one need to ask suppliers who in turn might need to do some calculations, etc…?

2.3 "Data-intensity requirement": To make the difference towards sub-criterion clear, it was agreed that the main question is: How much data is needed? This is independent of the question whether or not it is easy to get the data.

5.1 "Inclusion of positive and negative impacts": For criticality, positive impacts are relative but not necessarily visible in the final indicator score. For the sub-criterion 5.1, therefore, it is desirable that the method and thus its indicator considers efforts to reduce criticality (e.g. substitution and recyclability). If these efforts are not visible in the score in the end, then the method should rank lower than "A".

4 Analysis of specific topics related to material criticality in LC(S)A

In this report, we aim to analyse the way in which CRMs are currently assessed or could potentially be assessed in an operational LCSA framework to be developed in ORIENTING. Besides the evaluation of the existing methods, in this section we highlight the points of debate in the literature that are relevant to this project.

4.1 Mapping of critical materials and elementary flows in the LCI

A few attempts to implement criticality into LC(S)A have already been made (e.g. Bach et al., 2016b; Sonnemann et al., 2015). However, there is a fundamental difference between LC(S)A and the assessment of criticality that complicates the inclusion of CA in operationalized LC(S)A methodologies.

As stated in Cimprich et al. (2019), LCIA methods provide characterization factors (CF) that are applied (only) to elementary flows as contained in the life cycle inventory. According to ISO 14040, "elementary flows" are the flows that cross the boundary between the product system and the environment and may relate to use of resources (e.g. ores) as well as to releases. Regarding criticality, only the aspect "use of resources" is relevant. "Elementary flows" as regards use of resources are defined in ISO 14040 as material or energy entering the system being studied, drawn from the environment without previous human transformation.

In contrast to resource use impact assessments in LCA, criticality methods usually consider socio-economic aspects e.g. in terms of circular economy activities and regarding geopolitical situations (in addition to geological and/or environmental aspects) (UNEP, 2019a), which are driven by society i.e., within a *technosphere* system (in LCA terminology). Therefore, criticality related to supply risk associated with a product system is a function of its entire value chain. This also means that many of the relevant flows for supply risk assessment occur within the product system (e.g. when passing through more or less risky countries), and cannot be assessed solely on the basis of elementary flows. Rather, CFs for criticality methods would need to be applied (also) to intermediate flows (Cimprich et al., 2019). These are defined by ISO 14040 as product, material or energy flows occurring between unit processes of the product system being studied. For instance, Helbig et al. (2016) highlighted that the bottleneck in the supply of carbon fibre is in the imbalance between the supply and demand of the precursor chemical – polyacrylonitrile (PAN) – and proposed that the characterization of supply risk according to GeoPolRisk methodology should include the analysis of multiple-stages of the supply chain.

Therefore, an obstacle to the implementation of criticality assessments in an LC(S)A framework is that intermediate flows, notably in the background system, cannot be used as elementary flows, i.e., for the multiplication with the characterization factors. With the currently existing LC(S)A framework, there are two ways to proceed: either (i) one contents oneself with a criticality assessment that is limited to the analysis of primary resources (UNEP, 2019a) or (ii) one accepts that the criticality assessment is inconsistent, i.e., it connects e.g., socio-economic aspects to environmental flows (elementary flows). Of course, this limitation is related to the currently existing LCA structure, with LCA databases following the structure of ISO 14040, rather than to the way in which criticality is assessed. Nonetheless, a few solutions can be further explored in the ORIENTING project in collaboration with LCA database owners (e.g., Ecoinvent). For instance, evaluating the feasibility of creating connections between CFs at the LCIA stage to "technological" flows (i.e., intermediate product flows within the technosphere/product system) in the LCI.

4.2 Criticality as part of LCA, LCC, sLCA or LCSA?

Within the LCA community, no consensus exists whether the impact of using (i.e., not extracting) a resource should be evaluated as part of (environmental) LCA (Drielsma et al., 2016; Goedkoop, 1995; UNEP, 2019a). As also noted by UNEP (2019a), the area of protection "Natural Resources" by definition comprises environmental ("natural") and economic aspects ("resource"). The issue of the availability of resources or rather their depletion has been evaluated in environmental LCA for decades (Guinée, 1995). This was presumably also because it could be assessed with the help of the Life Cycle Inventory (LCI) generally created for evaluating environmental impacts. Beyond the environmental impacts caused by taking a resource from the environment, covered by dedicated impact categories, however, the issue assessed when dealing with availability is an economic, technical and/or political one (i.e., not only an environmental one) (Goedkoop, 1995).

The same debate applies to criticality. Criticality indicators do not evaluate resource depletion (although somehow related), but are deemed useful as complementary information (Drielsma et al., 2016; Klinglmair et al., 2014). There is no scientific consensus on best practice how to evaluate criticality neither in general nor from a product life cycle perspective (Schrijvers et al., 2020). Guidelines such as the recommendations by the JRC regarding the life cycle impact assessment methods to be used in the frame of the PEF/OEF (Zampori & Pant, 2019) are still needed.

There is, however, a general agreement that material criticality is not part of environmental LCA. The additional socio-economic and geopolitical issues related to natural resources incorporated by CA are relevant as sustainable supply aspects (Drielsma et al., 2016; Sonnemann et al., 2015). In this sense, according to some researchers, CA could be part of a more encompassing LCSA (Sonnemann et al. (2015), Dewulf et al. (2015), van Oers & Guinée (2016), Gemechu et al. (2016), Bach et al. (2016b) and Cimprich et al. (2019)). The authors that have attempted to draft the relationship of criticality parameters to the LCSA domains conclude that CA can have elements connectable to environmental (e.g. mineral and metal resource depletion and impacts on ecosystems quality), economic (e.g. economic importance due to percent of revenue impacted and cost increases) and social (e.g. geopolitical issues such as corruption and political stability, and labour conditions such as fair salary and health and safety) dimensions. These elements can be used to characterize criticality within LCSA, depending on the definition of material criticality. However, it is also important to highlight that the LCA methodological steps have given rise to divergent arguments in the literature. for Sonnemann et al. (2015), the LCA-related elements in different CA methods are the depletion indicators and the inventory itself. Following the same reasoning, Mancini et al. (2016) argue that criticality aspects could be better introduced as (environmental) LCA due to use of biophysical elementary flows in the LCI, despite the socio-economic aspects. These are rather technical arguments regarding LCA practices. They are relevant to the operationalization of criticality indicators in LCSA, but should not restrict the understanding of what these indicators aim to convey, which includes the effect of economic and social aspects on the risks of supply disruption.

Although the pathway to a separate sustainability dimension could not be supported, the three supply risk methods within the scientific LCA or Material Flow Assessment domain - highlighted by UNEP (2019a) and cited previously in this report (ESSENZ, ESP, GeoPolRisk) – advocate for the inclusion of criticality in a LCSA framework. Which method(s) to explore further and in which way will be discussed in chapter 6.

4.3 The use of subjective elements when defining criticality

As stated in chapter 2, CRMs are usually defined in terms of supply risk (Gemechu et al., 2016), supply risk and vulnerability (Cimprich et al., 2019; European Commission, 2017b, 2020c; National Research Council, 2008), or even including a third indicator (e.g. environmental (Graedel et al., 2012; Mudd et al., 2018)) or yet further indicators (Hatayama & Tahara, 2015).

Where more than one indicator is used, classifying a raw material as "critical" is either defined as indicators exceeding a threshold (European Commission, 2017b; Hatayama & Tahara, 2015) or relating indicators to targets elicited in surveys (Bach et al., 2016b), as a summation after weighting[3] (Graedel et al., 2012; Hatayama & Tahara, 2015), or with the help of a merely graphical representation of the indicators (National Research Council, 2008). In the last two cases, the results are represented by the "criticality vector magnitude" (Graedel et al., 2012). However, in any of those cases the "criticality area" (or range) represents an element of subjectivity (Mancini et al., 2016), either based on the opinion of experts or on the comparison among materials analysed. That can be a source of uncertainty to the CA given that "critical" becomes a relative concept subjected to the questions: to whom?; where?; and when? (Mancini et al., 2013). In addition, ISO 14040 requires to base decisions within an LCA on natural science as one of the main principles (see sub-clause 4.1.8 in ISO, 2006a). ISO 14044 further recommends to minimise value-choices in characterisation models (see sub-clause 4.4.2.2.3 in ISO, 2006b).

A solution to the reduction of subjectivity in the creation of CFs from results of CA, such as the EC-CA (European Commission, 2020c), is the characterization of indicators regardless of the thresholds set. This was already proposed by Mancini et al. (2016), which relied only on the use of the supply risk indicator from the EC-CA, and by Tran et al. (2018), which considered results of both indicators from the EC-CA aggregated into a single value. The use of thresholds as normalization or weighting factors for the interpretation of results was not yet explored but could also represent a solution (e.g. computing the two indicators that the EC-CA relies upon without thresholds by default and then allowing the use of thresholds/weighting factors as an optional element).

Finally, it needs to be noted that the ISO standards mainly concern environmental LCA, while ORIENTING's LCSA framework goes beyond the environmental dimension. Thus, the rules for the use of normalization and weighting practices at the interpretation step may be revisited and adapted to this end.

4.4 Dynamics of raw materials' supply chain

Another issue in the integration of criticality in the LC(S)A impact assessment is the rapid changes that may occur in CRMs supply chain (Mancini et al., 2013). Material supply chain patterns are highly dynamic and complex (Achzet & Helbig, 2013; Cimprich et al., 2019; Vogtländer et al., 2019). Aspects that can constrain the access to resources are related to changes for example in demand, technological development, access to land and mineral deposits, as well as to other site-specific geopolitical aspects, such as political stability (Drielsma et al., 2016; Mancini et al., 2015). For instance, the methods GeoPolRisk, ESP and ESSENZ provide a snapshot of estimated supply risk related to these aspects at a given point in time (Cimprich et al., 2019). This static modelling does not encompass the interrelated aspects affecting criticality, such as the feedbacks between demand and supply or their effects on the dependent systems where this materials are used during time

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[3] Graedel et al. (2012) also use normalisation.

(Knoeri et al., 2013). While all CFs used in LCIA are representative of a given situation and are subject to change (e.g. Krewitt et al., 2001; Lueddeckens et al., 2020), socio-economic systems can be expected to change more rapidly, unless tipping points in the natural environment are exceeded.

As a potential solution, in their review on dynamic criticality assessments, Ioannidou et al. (2019) suggest using prospective LCA supported by tools such as Dynamic Material Flow Analysis and System Dynamics to add dynamic elements to the analysis. In this way, variable parameters could be estimated using distribution functions and have their future values projected. However, dynamic assessments are also limited. For example, a long-term prospective assessment for resource demand, substitution and/or recycling rate are intrinsically based on theoretical assumption that increase results uncertainties. Besides, according to Achzet and Helbig (2013), the use of static models between 1993 and 2013 demonstrated that Cas have “almost stable” criticality results (i.e., CRMs tend to remain critical over the time).

The literature suggests overcoming the limitations of both static and dynamic modelling approaches to address the rapid changes in the system by conducting CA periodically such that the list of CRMs is frequently updated (Graedel & Reck, 2016; Ioannidou et al., 2019). That is, for example, the practice adopted by the European Commission that updates the CA and CRMs list every 3 years to track changes in the criticality.

Regarding prospective studies, which is another aspect addressed by the dynamic assessments, the European Innovation Partnership (EIP) on Raw Materials, a European Commission initiative to promote mid- to long-term sustainable supply of raw materials, had also set the goal to develop a fully dynamic LCSA model that can link trends in supply and demand with economically exploitable reserves to evaluate different future scenarios (European Commission, 2012). According to Mancini et al. (2013), in the future, the development of this EIP modelling approach could help policymakers to be more proactive instead of reactive regarding raw materials policies.

4.5 Data Acquisition for the assessment of Critical Raw Materials

Data availability and quality are crucial for a robust and reliable assessment in any area. In CA, different sources of data can be used. In general, CA methods mainly rely on national geological surveys and information from the World Bank, which produces the Worldwide Governance Indicators (European Commission, 2020c; Gemechu et al., 2016; Graedel, Harper, Nassar, Nuss, et al., 2015; National Research Council, 2008). Dedicated scientific papers and industry reports are also used for the more context-specific data e.g. related to a specific sector such as the cobalt industry in EU (Godoy León et al. (2020); see also European Commission (2020c) and Hatayama et al. (2015)).

The EC-CA reports of the CRM list explicitly address data availability as an issue. According to European Commission (2020c), there is good coverage of publicly available data on global supply chains. However, there is a general lack of publicly available data on the market shares of raw materials and their substitutes. This might also be the reason why methods cannot easily be regionalized as suggested by Ioannidou et al. (2019) or made generic to any region or country as suggested by Graedel & Reck (2016). Indeed, the lack of publicly available data is a limiting factor of most CA since data availability affects the material coverage and the indicator selection, and thus the goal and scope (Schrijvers et al., 2020). Generally, the lack of data on real conditions is fulfilled by estimated values, which creates uncertainty. For example, some recycling rates (RR) to build the EU list of CRM are based on data from industry (e.g. aluminium RR are based on data from European Aluminum association), while others rely on estimates (e.g. antimony RR are based on UNEP and Delloitte estimates) (European Commission, 2020c). Dewulf et al. (2015) highlight that specific frameworks should be used where available because they already provide specific datasets.

In perspective of the integration of a criticality indicator into an operational LCSA framework, the uncertainty linked to the modelling data for the characterization of material criticality should be properly addressed. In this sense, the use of existing criticality indicators, e.g. SR and EI from the EC-CA, must address the consistency between the modelling data and inventory data (as discussed in section 4.1), as well as to the updated data (discussed in section 4.4).

4.6 The connection between Material Criticality and Circular Economy

To be able to support the transition towards circular economy, it is necessary to improve the analysis of resource flows within sectors and products (Rigamonti et al., 2017). Circular economy (CE) strategies such as recycling and reuse are key actions to reduce the overall criticality of raw materials in terms of supply risks for the EU. The introduction of more efficient recycling processes for raw materials recovery, for example, could increase the supply of secondary raw materials in substitution to the virgin materials (Ardente et al., 2019). Besides increasing resource efficiency, promoting recycling is in fact one of the key strategies of the European Raw Materials Initiative to restrain the supply risk of CRMs (European Commission, 2020c).

Recycling rates have already been addressed by several CA methods, within LC(S)A, e.g. Gemechu et al. (2016) and Adibi et al. (2017), and outside the scope of LC(S)A, e.g. the EC-CA method (European Commission, 2017b) and the NEDO Japanese method (Hatayama & Tahara, 2015). The rates appear as mitigating factors within most of these supply risk indicators. Adibi et al. (2017), on the other hand, propose to introduce Recyclability as an independent indicator combined with Geopolitical Availability and Scarcity to compose a Global Resource Indicator. However, Rigamonti et al. (2017) noted that some resources that can be recycled and reused (e.g. on the recovery of electric and electronic waste) cannot be assessed with the help of existing LC(S)A characterization models, potentially due to issues regarding the characterization of intermediate flows discussed in section 4.1. Notwithstanding potential modelling issues, the International Round Table on Materials Criticality sees the common grounds of CE approach as a means to potentially mitigate criticality, not only through recycling but also through the integrated design strategies that can extend products' lifespan and reduce overall consumption of virgin raw materials (Tercero Espinoza et al., 2020). For a more in-depth discussion of CE strategies, see also Part 2 of this deliverable (chapters 7 to 11).

5 Evaluation of different material criticality approaches according to the ORIENTING criteria from T1.1

Table 7 provides an overview on the scoring of the different material criticality approaches. The evaluation of each individual approach for material criticality assessment against the evaluation criteria from T1.1 is presented in the following sections. As already stated in section 3.1, all evaluated methods address criticality in terms of supply risk. A more detailed description of the methods can be found in Annex B, section 13.2.

Table 7: Overview on the scoring of the different material criticality approaches

#	(Sub-) Criterion	NRC	EC-CA	Yale	ESSENZ	UK GS	NEDO	GeoPolRisk
III	Source	(National Research Council, 2008)	(European Commission, 2017)	(Graedel et al., 2012)	(Bach et al., 2016b)	(Shaw, 2015)	(Hatayama & Tahara, 2015)	(Gemechu et al., 2017)
XVII	**Overall Score**	**C+**	**A**	**A-**	**B+**	**B**	**B+**	**A**
1	**Stakeholder acceptance, credibility and suitability**	**B-**	**A+**	**A**	**B**	**B**	**B**	**B**
1.1	Acceptance by Policy-makers	*D*	*A*	*N/A*	*N/A*	*C*	*D*	*N/A*
1.2	Acceptance by Industry	*A*	*A*	*B*	*B*	*C*	*C*	*B*
1.3	Acceptance by Academia	*B*	*A*	*A*	*A*	*B*	*A*	*B*
1.4	Acceptance by Civil society	*N/A*	*N/A*	*N/A*	*N/A*	*N/A*	*N/A*	*N/A*
1.5	Credibility among stakeholders	*D*	*B*	*B*	*D*	*B*	*B*	*C*
2	**Applicability / Complexity**	**C+**	**A+**	**B**	**B+**	**A**	**A+**	**A+**
2.1	Technical feasibility	*A*	*A*	*A*	*B*	*A*	*A*	*A*
2.2	Data availability and accessibility	*N/A*	*A*	*C*	*N/A*	*B*	*A*	*A*
2.2.a	for primary data (activity data)	*N/A*	*N/A*	*N/A*	*C*	*N/A*	*N/A*	*N/A*
2.2.b	for secondary data (activity data)	*D*	*N/A*	*N/A*	*A*	*N/A*	*N/A*	*N/A*
2.3	Data-intensity requirement	*D*	*A*	*C*	*B*	*N/A*	*A*	*A*
2.4	Interoperability	*N/A*	*N/A*	*N/A*	*B*	*N/A*	*A*	*A*
3	**Transparency**	**C**	**A+**	**A**	**B+**	**B**	**B+**	**A**
3.1	Traceability of the modelling data and model used	*D*	*A*	*B*	*B*	*B*	*D*	*A*
3.2	Transparency of documentation	*C*	*A*	*A*	*B*	*B*	*A*	*A*
3.3	Reproducibility	*C*	*A*	*B*	*B*	*C*	*A*	*C*
4	**Scientific robustness**	**C**	**B+**	**A-**	**A-**	**C+**	**B**	**A**
4.1	Peer-reviewed or verification by 3rd party	*E*	*B*	*A*	*A*	*D*	*A*	*A*
4.2	State-of-the-art	*C*	*B*	*B*	*B*	*B*	*B*	*B*
4.3	Quality of the modelling data	*C*	*B*	*B*	*A*	*B*	*B*	*B*
4.4	Description of the uncertainties	*C*	*C*	*B*	*C*	*E*	*E*	*A*
5	**Completeness**	**B**	**A+**	**A**	**B-**	**A**	**A**	**A+**
5.1	Inclusion of positive and negative impacts	*C*	*A*	*A*	*E*	*A*	*A*	*A*
5.2	Ability to be applied to EU context	*C*	*A*	*B*	*C*	*B*	*C*	*A*
5.3	Degree to which the approach assesses material criticality	*A*	*A*	*A*	*A*	*A*	*A*	*A*
6	**Compatibility with life-cycle approach**	**C+**	**C+**	**C+**	**B+**	**C+**	**C+**	**B+**
6.1	Life cycle thinking/ approach	*C*	*C*	*C*	*B*	*C*	*C*	*B*

5.1 U.S. National Research Council (NRC)

NRC

CRITICALITY

SCORE **C+**

DESCRIPTION

This framework allows the assessment of supply risk and impacts of supply restrictions for minerals in a 2-dimensional space (matrix) (National Research Council, 2008). For supply risk (x-axis), 5 different aspects of availability are considered (covering primary as well as secondary resources). For impacts of supply restrictions (y-axis), a weighted composite score is used. The outcome of the methodology is the placement in the matrix, defining the degree of criticality. Intended audience is federal agencies, industry, research organizations, and decision makers. It has been used for investigation of importance of non-fuel minerals in the U.S., as for definition and identification of "critical", long and short term availability.

DEBATE

Pioneer among CA methodologies. Its framework approach of criticality matrix was accepted (and adapted) by other bodies (e.g. EU). Criticality can vary over time depending on factors such as production, world market, technology development. Assumptions from 2008 are rather outdated. In comparison, the EU publishes updates on their CRM assessment every three years in terms of data and methodology.

CRITERIA

1. Stakeholder acceptance, credibility and suitability

The methodology is endorsed by one non-EU governmental body (U.S.) and is widely applied in industrial sectors and industry research. It is recognised by the International Round Table on Materials Criticality. An adapted framework is well recognised within the European Union (Mancini et al., 2016). The methodology can only be understood and reproduced by specialists.

SCORE B-

2. Applicability / Complexity

Calculation can be done with standard freely available software. The published data is very outdated and the gathering of new data might be restricted due to confidentiality issues. To generate criticality scores, a lot of foreground activity data is required.

SCORE C+

3. Transparency

Methodological specifications are available but incomplete. Methodological choices are only partially stated and/or they are ambiguous. Results could be reproduced, but would require additional methodological choices and data collection.

SCORE C

4. Scientific robustness

There is no documentation stating any peer-review status or verification by third party. The methodology has not been updated in the last 10 years, but contains robust timeless

COMMENTS

National Research Council (2008) assume that criticality is best regarded as a continuum of possible degrees and not as a yes/no answer because it is context specific.

The methodology is not independent, as it uses economic, social and environmental indicators.

knowledge. Quality of the modelling data is unclear. Uncertainty estimates are provided, motivated and reported in qualitative terms.

SCORE C

5. Completeness

Next to negative impacts consideration, recyclability and substitution are considered as well. The methodology can be applied to the EU with modification. It assesses criticality in terms of supply risks.

SCORE B+

6. Compatibility with life-cycle approach

The methodology could fit with LCA structure after adjustments in terms of mapping flows with elementary flows from LCA (see section 4.1).

SCORE B+

5.2 European Commission Criticality Assessment – EU CRM list

European Commission Criticality Assessment – EU CRM list CRITICALITY

SCORE **A**

DESCRIPTION

The EC criticality methodology (European Commission, 2017b) was developed to assess the criticality of important raw materials for the EU and is based on two indicators: Supply Risk and Economic Importance. Every three years, the assessment provides a list of Critical Raw Materials (CRM) based on a threshold set for each indicator, in order to analyse the key trends and identify potential supply risks. The final results are qualitative (“critical” or “non-

CRITERIA

1. Stakeholder acceptance, credibility and suitability

The methodology is endorsed by the EU and by several industrial economy sectors. It is also well recognised by international research bodies as well as the International Round Table on Materials Criticality. The methodology can easily be understood and reproduced by those with basic knowledge in the field, namely materials engineering.

SCORE A+

critical"), but intermediate scores for the two indicators are also available. The intended audience is all industry sectors in the EU with high import dependency for materials and policymakers.

DEBATE

Since the indicators calculated are based on market values or indexes, their values are not directly relatable to flows in a product-level analysis (see the electronic supporting material of Mancini et al. (2016) for the discussion of SR (Supply Risk) characterization factors in LCA and also section 4.1).

COMMENTS

The method does not require any particular software/tool and is updated every 3 years.

The methodology is not independent, as it uses economic indicators, which can overlap with LCC approaches.

2. Applicability / Complexity

Calculation can be done with standard freely available software. General data is available for free in appropriate formats without restrictions. To generate results, very little foreground activity data is required.

SCORE A+

3. Transparency

Full methodological specifications are continuously available. All methodological choices are clearly documented. Results can easily be reproduced.

SCORE A+

4. Scientific robustness

The methodology has been peer-reviewed, in the context of validation workshops. It is continuously updated and contains robust timeless knowledge. The available data has acceptable representativeness and/or quality. Uncertainty estimates are provided, motivated and reported in qualitative terms.

SCORE B+

5. Completeness

Both positive (recycling and substitution) and negative impacts are included in the analysis. The methodology can be applied to the EU without modification. It assesses criticality in terms of supply risks.

SCORE A+

6. Compatibility with life-cycle approach

The methodology could fit with LCA structure after adjustments in terms of mapping of flows with elementary flows from LCA (see section 4.1).

SCORE C+

5.3 Yale (Methodology of Metal Criticality Determination)

Yale (Methodology of Metal Criticality Determination) Criticality

SCORE A-

DESCRIPTION

Methodology for determining the criticality of metals, mainly from a use perspective (Graedel et al., 2012). It addresses corporate, national and global levels, medium and long-term dimensions and uses indicators for the dimensions “supply risk”, “environmental implications” and “vulnerability to supply restrictions”. In various publications, it has been applied to a range of elements, also relating to criticality of water or construction aggregates. The methodology provides quantitative time-dependent results in form of a single score indicator (after aggregation and normalization). Results are typically displayed in a 3-dimensional space to account for all 3 dimensions.

DEBATE

Methodologically, uncertainty and limitations related to data availability and consistency can be mentioned, just as (subjective) choices of the indicators use and concerning aggregation; inclusion of environmental implications is debated; not directly applicable to composite compounds. However, these are general aspects that also apply to other methodologies and they are transparently dealt with by the authors.

CRITERIA

1. Stakeholder acceptance, credibility and suitability

The methodology should be well suited for policy-making and corporate users but no concrete policy endorsement was found. With over 300 citations, it is also well recognised by international research promoters/bodies. It is recognised by the International Round Table on Materials Criticality. On Materials Criticality. The methodology can easily be understood and reproduced by those with basic knowledge in the field.

SCORE A

2. Applicability / Complexity

Calculation can be done with standard freely available software tools. General data is available for free and in appropriate formats, but specific (up-to-date) data from an industry and/or company may be required. Depending on the application, medium foreground activity data is required to generate results.

SCORE B

3. Transparency

Full methodological specifications are continuously available. All methodological choices are clearly documented. For reproducibility, detailed supplementary materials are available.

SCORE A

COMMENTS

This methodology is an extension of work by the US National Research Council (2008); for this methodology detailed supplementary information are available e.g. see references in section 13.2.1. There is an overlap with the environmental pillar (environmental implications) and for the corporate level, also the economic pillar (e.g. possibility to pass through cost increases). Double-counting could potentially be avoided if environmental implications (cradle-to-gate impacts of metal supply) were solely reported under the environmental pillar (related to LCA results). Yet, it seems preferable not to alter the 3-dimensional result space of this criticality methodology and to transparently mention “double counting” issues, if relevant.

4. Scientific robustness

The methodology has been peer reviewed or verified by third party. It is continuously updated. The available data has acceptable representativeness and/or quality.

SCORE A-

5. Completeness

Both positive and negative impacts are included in the analysis. The methodology can be applied to the EU, depending on data availability. Material criticality is assessed in terms of supply risk.

SCORE A

6. Compatibility with life-cycle approach

The methodology could fit with LCA structure after adjustments in terms of mapping of flows with elementary flows from LCA (see section 4.1).

SCORE C+

5.4 ESSENZ

ESSENZ

Criticality

SCORE **B+**

DESCRIPTION

The ESSENZ method (Bach et al., 2016b), which enhanced the preceding ESP method (Schneider et al., 2014), quantifies eleven geopolitical and socioeconomic accessibility constraints (i.e., country concentration of reserves and mine production, price variation, co-production, political stability, demand growth, feasibility of exploration projects, company concentration, primary material use, mining capacity, and trade barriers). Indicators

CRITERIA

1. Stakeholder acceptance, credibility and suitability

No evidence for endorsement or applications by public authorities was found. However, it is included as an interim recommendation of Phase 2 of GLAM for global level assessments of criticality. The method was developed in a consortium with strong industrial participation. Therefore, a certain industry acceptance can be assumed.

SCORE B

for these categories are determined and divided by a target value above which accessibility constraints are assumed to occur. This distance-to-target (DtT) ratio is normalized by the global production of the respective resource to reflect the assumption that the accessibility constraints described above can be more severe for resources produced in relatively small amounts. Finally, the normalised DtT factors are scaled to a range based on the largest production volume considered.

Results are presented for 19 categories, of which 11 are criticality related. Single score calculation is possible but not recommended by the developers.

DEBATE

Main critique is the restriction of CFs to global level only, and limitation to primary resources.

COMMENTS

Data is mainly gatherable by the organisation applying the method, but exceeds publicly available data. Specific CF calculation is complex and requires very comprehensive

2. Applicability / Complexity

Excel based tools are provided by the developers, still expert knowledge and tools are necessary for application. CFs are available for 49 minerals, 4 energy carriers and 7 other resources.

SCORE B+

3. Transparency

Full methodological specifications are continuously available. Results can be reproduced with a relatively high effort.

SCORE B+

4. Scientific robustness

The relatively recent method had no major update yet (but working group still active). The method was published in peer reviewed publications and has an interim GLAM recommendation. The available data has high representativeness and quality but uncertainty issues are only qualitatively addressed.

SCORE A-

5. Completeness

Criticality is covered in terms of supply risk but only negative impacts are considered. While it is possible to calculate specific CFs, only global level CFs are available.

SCORE B-knowledge of the methodology (Bach et al., 2016a).

The methodology is not independent, as it uses economic indicators (i.e., price fluctuations), which can overlap with LCC approaches.

6. Compatibility with life-cycle approach

The method is made for LCA, nevertheless there are some issues regarding elementary flows (see section 4.1).

SCORE B+

5.5 British Geological Survey – Supply Risk Index

British Geological Survey – Supply Risk Index

CRITICALITY

SCORE **B**

DESCRIPTION

This methodology by the British Geological Survey (Shaw, 2015) estimates the relative risk of supply of chemical elements, based on seven criteria (each scored 1 to 3). A supply risk index is obtained by adding all criteria score values and normalizing the results.

The main output is a Supply Risk ranking for 41 elements (or group of elements) considered of economic value by the British Geological Survey. It gives policy-makers, industries and consumers an indication of which element might be subject to supply disruption.

DEBATE

There are concerns about proxy data and related information reliability (Schrijvers et al., 2020). It is difficult to directly link the politically stability surveys and studies with the potential for protectionist trade policies or restrictive environmental policies that may

CRITERIA

1. Stakeholder acceptance, credibility and suitability

The methodology is endorsed by one governmental body (UK Government, i.e., not by the EU) and partially accepted by industry. Being cited in scientific/academic works, it is recognised within the scientific community. The methodology can be understood/reproduced by researchers with basic knowledge in the field.

SCORE B

2. Applicability / Complexity

Calculation can be done with standard freely available software. General data is available (either in appropriate formats or formats like pdf or hard copies) with some restriction.

SCORE A

3. Transparency

Full methodological specifications are continuously available. Methodological choices are well explained. The results might be reproduced based on existing data (additional choices and data required).

SCORE B

affect material supplies. The analysis needs to be more intrusive and specific to the individual circumstances, unique to each metal and each country, in order to produce an effectual conclusion. On the other side, the evaluation according to this method is kept simple with the aim to merely highlight a potential dependency issue.

COMMENTS

As for other evaluated methods, there are aspects of the methodology overlapping with the societal and environmental sustainability pillars.

4. Scientific robustness

No documentation stating the peer-review status or verification by third party is available. However, it can be considered of high quality. The available data has acceptable representativeness and/or quality. Uncertainty estimates are not provided.

SCORE C+

5. Completeness

Positive (recycling and substitution) and negative impacts are included in the analysis of the product. The methodology cannot be modified and applied to the EU, due to its generalized (global) context. It assesses criticality in terms of supply risks.

SCORE B

6. Compatibility with life-cycle approach

The methodology could fit with LCA structure after adjustments in terms of mapping of flows with elementary flows from LCA (see section 4.1).

SCORE C

5.6 NEDO (Japan's criticality assessment)

NEDO (Japan's criticality assessment)
CRITICALITY

SCORE **B+**

DESCRIPTION

The methodology is used to evaluate "strategic minerals" for Japan (Hatayama & Tahara, 2015). It evaluates five risk categories (i.e., Supply risk, Price risk, Demand Risk, Recycling restriction and Potential Risk) by means of 12 indicators. Each indicator ranges from 0 to 3 points. The maximum criticality score can be 32 points, as risk categories are weighted unequally. Minerals with 18 points or higher

CRITERIA

1. Stakeholder acceptance, credibility and suitability

The methodology is endorsed by one non-EU governmental body (Japan) and partially accepted by industry. It is recognised by the International Round Table on Materials Criticality. It can easily be understood and reproduced by those with basic knowledge in the field.

SCORE B

are classified as “strategic”. Final scores and intermediate values can both be visualized. Hatayama and Tahara (2015) suggest an additional indicator. The intended audience is all industry sectors in Japan with high materials import as well as policymakers.

DEBATE

Although the assessment report by Hatayama and Tahara (2015) did not use the terms “criticality” or “critical metal/ material”, the assessment evaluated the critical metals for Japan. They further state that the NEDO assessment framework does not reflect a difference in degree of resource security.

COMMENTS

The methodology requires basic knowledge on materials engineering for the analysis of recyclability.

The used indicators can overlap with LCA (depletion time), LCC (price changes) and CE.

2. Applicability / Complexity

Calculation can be done with standard freely available software. General data is available for free in appropriate formats without restrictions. To generate results, very low foreground data is required. The software/databases allow the conversion of files.

SCORE A+

3. Transparency

Methodological specifications are available but incomplete. All methodological choices are clearly documented. Results can easily be reproduced.

SCORE B+

4. Scientific robustness

The methodology has been peer reviewed or verified by third party. The methodology is not been updated since 2015. The available data has acceptable representativeness and/or quality. Uncertainties are neither documented nor could related information be found.

SCORE B

5. Completeness

Positive and negative impacts are included in the analysis of the product system. The methodology can be applied to the EU with modification. It assesses criticality in terms of supply risks.

SCORE A

6. Compatibility with life-cycle approach

The methodology could fit with LCA structure after adjustments in terms of mapping of flows with elementary flows from LCA (see section 4.1).

SCORE C+

5.7 GeoPolRisk

GeoPolRisk

Criticality

SCORE A

DESCRIPTION

Proposed by Gemechu et al. (2016), this import-based indicator for the Geopolitical Supply Risk (GeoPolRisk) of resources aims to add a supply risk perspective within the LCSA framework. It is based on Herfindahl-Hirschman Index (HHI) and the World Bank's Worldwide Governance Indicators (WGI). Relying on these indicators and taking the perspective of the resource demanding country, it allows considering: the global share of a supplying-country in the production of a certain commodity, the geopolitical stability of this country and the import share of the demanding-country from the supplying-country. Later time proposals added the second stage to the supply-chain analysis (Cimprich et al., 2017, 2019; Santillán-Saldivar et al., 2021).

The assessment is focused on raw materials. However, it aims to provide information at a component/product production level. The intended audience is all industry sectors, policy-makers and LCA practitioners.

DEBATE

Critics mention the primary focus on the socioeconomic aspects while often there is an overlap with environmental mechanism (Sonderegger et al., 2020). Another point is the complexity of supply risk assessment at country level, though it is more narrowly focused on supply risks arising from political (in)stability of trade

CRITERIA

1. Stakeholder acceptance, credibility and suitability

The method is an interim recommendation of Phase 2 of GLAM and is recognised by the International Round Table on Materials Criticality. No policy endorsement could be found. Only basic knowledge of LCA is required for application.

SCORE B

2. Applicability / Complexity

The GeoPolRisk characterisation factors can be calculated in spreadsheets. In some cases, this can be quite complex depending on the volume of data. However, the release of a free and public python tool is planned and might further improve technical feasibility. The associated data collection requirement is, therefore, assumed to be pretty low and general data is available for free.

SCORE A+

3. Transparency

Transparency is high as methodological choices are clearly documented. Regarding data availability, product specific data might not freely available. Results can be reproduced, but in some cases, this might require enormous efforts.

partners from which inventory flows are imported (Cimprich et al., 2019).

COMMENTS

The method is made for LCA, but still, there are some issues regarding elementary flows (see section 4.1).

Despite the (yet) accessible data, transparent calculations and only basic methodological requirements, special cases can still get very complex and result into enormous efforts e.g. for the number of different supply-chain paths (Santillán-Saldivar et al., 2021).

SCORE A

4. Scientific robustness

The methodology has been verified by a third party and is continuously updated. Uncertainty estimates are motivated and reported, and covered in corresponding literature. The available data has acceptable representativeness and quality but depending on the specific product under investigation issues with data availability might occur.

SCORE A

5. Completeness

The methodology assesses criticality in terms of supply risk. Through substitution and recyclability, positive and negative impacts are included. It can be applied in the EU without modification as it works on sector/company and product level. Regional data might still be needed.

SCORE A+

6. Compatibility with life-cycle approach

The method is made for LCA, nevertheless there are some issues regarding elementary flows (see section 4.1).

SCORE B+

6 Conclusions

According to ORIENTING's Description of Work, the "ultimate goal" regarding criticality metrics is "to provide a material-focused LCSA methodology that includes assessing criticality as one of the key elements motivating a circular economy". While acknowledging that criticality can be assessed in different ways (Sonderegger et al., 2020), criticality here is assessed in terms of supply risks (and economic importance when relevant; see section 2.2).

After pre-selection (see section 3), seven methods have been evaluated against the T1.1 criteria:

1. National Research Council (NRC) (National Research Council, 2008),
2. European Commission's Critical Raw Material methodology (here referred to as European Commission's Criticality Assessment, EC-CA) (European Commission, 2017b, 2020c),

3. Yale methodology (Graedel et al., 2012), including extensions (Graedel, Harper, Nassar, & Reck, 2015; Ioannidou et al., 2017),
4. ESSENZ (Bach et al., 2016b),
5. British Geological Survey (Shaw, 2015),
6. Japan's Resource Strategy (NEDO) (Hatayama & Tahara, 2015) and
7. GeoPolRisk (Cimprich et al., 2017, 2018; Gemechu et al., 2016).

While recommendations as to which of these methods should be further analysed in WP2 are given in section 6.2, a few more general issues shall be discussed at first. The following issues have been identified and discussed in Chapter 4: (i) Mapping of critical materials and elementary flows in the LCI; (ii) Criticality as part of LCA, LCC, sLCA or LCSA?; (iii) The use of subjective elements when defining criticality; (iv) Dynamics of raw materials' supply chain; (v) Data Acquisition for the assessment of Critical Raw Materials; and (vi) The connection between Material Criticality and Circular Economy. Two of these "issues" are dealt with in Part 2 of this deliverable, i.e., (ii) the question to which of the three pillars of sustainable development circularity belongs (see section 4.2) is dealt in the next section (6.2), while the (vi) existing link between criticality and circularity is evident (see section 4.6). Part 2 of this deliverable deals with circularity in more detail.

6.1 Issues to be potentially addressed in WP2

The first issue concerns the kind of input data needed (see section 4.1). While criticality assessments largely use input data that can also be found in conventional LCIs, their granularity is not sufficient to trace the paths of the materials from resource extraction over potentially various steps in the manufacturing and retailing stages to the final consumers. At the current level of development of integrated LC(S)A and CA analysis, two solutions to this problem are conceivable: either (i) one contents oneself with a criticality assessment that is limited to the analysis of primary resources (UNEP, 2019a) or (ii) one accepts that the criticality assessment is inconsistent, i.e., it connects e.g., socio-economic aspects to environmental flows (elementary flows). Nonetheless, WP2 of the ORIENTING project will explore further improvements in the links between CFs and the elementary and intermediate flows in the (environmental) LCI to increase consistency of the use of criticality indicators in LCSA (as suggested in section 4.1).

The next issue, as raised by Mancini et al. (2016), is about subjectivity included in defining whether or not a material is critical (see section 4.3). In drawing a final conclusion, subjective elements come either in the form of non-scientific thresholds or targets (Bach et al., 2016b; European Commission, 2017b) or in the form of weighting of different indicators (e.g. Graedel et al., 2012). As one of the main principles, ISO 14040 requires to base decisions within an LCA on natural science (see sub-clause 4.1.8 in ISO, 2006a). ISO 14044 further recommends to minimise value-choices in characterisation models (see sub-clause 4.4.2.2.3 in ISO, 2006b). While acknowledging that it is somewhat a binary choice to classify a material as critical or non-critical (i.e., involving some kind of dividing line), WP2 of the ORIENTING project could explore ways to characterise criticality on a continuous (cardinal) scale, distinguishing between different degrees of criticality. The work might be inspired by Mancini et al. (2016) or Tran et al. (2018). On the other hand, the ISO standards mainly concern environmental assessments, while ORIENTING's LCSA framework goes beyond the environmental domain.

As with evaluations of other issues (e.g. environmental impacts), dynamic aspects (i.e., inter-annual variability and prospective assessments) also concern criticality (see section 4.4). While inter-annual variability could be addressed by regularly (frequently) updating the assessment, prospective assessments require modelling efforts with substantial use of assumptions. To which extent this can be addressed in WP2 of the ORIENTING project still needs to be seen. If, however, characterisation factors (CFs) are created or taken from any one of the criticality assessments prioritised and evaluated in chapter 5 and recommended in section 6.2, ORIENTING might facilitate the updating of these CFs in the course of time by providing one or several respective tools.

Available data of a sufficient quality is always important and so it is for criticality. "Data availability and accessibility" has been evaluated for activity data[4] as sub-criterion 2.2 in chapter 5. Data needs for assessing whether or not a given material is critical, by contrast, is another issue (see section 4.5), to be further considered in WP2.

6.2 CA method(s) recommended for consideration in WP2

The evaluation against the T1.1 criteria in chapter 5 suggests that almost all analysed methods for the assessment of criticality have a relatively high rating, i.e., between A and B, except for NRC scoring C+. The highest score (A) has resulted for EC-CA and GeoPolRisk. This overall score as resulted from assigning equal weight to all sub-criteria and averaging over the sum of their scores. The question, however, is whether all sub-criteria should be assigned equal importance.

The ORIENTING project seeks to develop "*a robust and operational methodology for the life cycle sustainability assessment (LCSA) of products and services*" (taken from the DoW's abstract). In terms of criticality, ORIENTING aims to "*develop characterisation factors for assessing criticality by relying on the methods and results as in European Commission […] and by actively cooperating with ongoing activities led by the JRC. These characterisation factors will be compatible with existing material inventories used in Environmental LCA. The ultimate goal is to provide a material-focused LCSA methodology that includes assessing criticality as one of the key elements motivating a circular economy*" (taken from section 1.4.1 of the DoW). This means that key features should be operationality (addressed by the criteria 2 "applicability", and 6 "Compatibility with life-cycle approach"), as well as alignment with the European Commission's criticality evaluation (addressed by sub-criterion 1.1 "Acceptance by Policy-makers") (note the issue regarding the mapping of the critical materials with elementary flows in section 4.1).

For operationality in terms of applicability, EC-CA, GeoPolRisk and the Japanese NEDO assessment rank highest (A+). The two methods developed in an LCSA context, i.e., GeoPolRisk and ESSENZ, score highest (B+) for compatibility with the life cycle approach (including aspects of operationality). When it comes to acceptance by (EU) policy makers, only EC-CA is assigned the highest score (A). With the exception of GeoPolRisk, all methods overlap at least with one of sustainability pillar (issue of potential double-counting). In addition, the EC-CA, ESSENZ and NEDO methods involve the use of subjective elements (thresholds, targets and/or weights) that should be avoided in LCA according to ISO (ISO, 2006a, 2006b). It needs to be seen in WP2 to which extent subjective elements will be allowed in the non-environmental parts of the LCSA framework. An important element will be to make the subjective elements, if any, transparent. As a final note, in terms of scientific robustness, the most promising methods are GeoPolRisk (A), closely followed by ESSENZ and Yale method (A-), and by the EC-CA (B+).

Putting aside the subjectivity of the mathematical procedure that allowed the generation of the overall score of the evaluations, EC-CA and/or GeoPolRisk, therefore, appear indeed to be the two approaches to be further

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[4] For the purpose of the evaluation of the methods against the T1.1 criteria, the term "activity data" refers to information which is associated with processes while modelling Life Cycle Inventories (LCI). The aggregated LCI results of the process chains that represent the activities of a process are each multiplied by the corresponding activity data and then combined to derive the environmental footprint associated with that process. Examples of activity data include quantity of kilowatt-hours of electricity used, quantity of fuel used, output of a process (e.g. waste), number of hours equipment is operated, distance travelled, floor area of a building, etc. Synonym of "non-elementary flow".

explored in WP2, noting the issue of subjective thresholds. As suggested in ORIENTING's DoW and following Tran et al. (2018), an idea could be to integrate the two dimensions by which EC-CA assesses criticality into a single characterisation factor per material. Another idea could be to explore the extent to which one of the methods could be improved by features of the other (e.g. improving EC-CA in terms of LCA-alignment). The challenges to properly address the pathways that the materials take during their journey from their source to the final product is yet another development path, noting that this may go beyond the scope of the ORIENTING project (see section 4.1). Temporal variability should at least be accounted for by facilitating regular updates. Making the suggestions on how to conduct prospective analyses appears to be out of the scope of the ORIENTING project.

6.3 How to integrate CA into the ORIENTING's LCSA?

As already discussed in section 4.2, there are links between criticality and the three pillars of sustainability. Seeing criticality as part of (environmental) LCA due to the mere fact that it relies on the same LCI data as suggested by Mancini et al. (2016) is a technical not a content (or "sustainability domain") related argument. The argument that (virgin) material use leads to resource depletion and impacts on ecosystems does not apply either given that environmental LCA in general and the PEF methodology in particular (Zampori & Pant, 2019) provide or foresee dedicated impact categories for these implications. As long as there is no double-counting with these assessments (as would be the case when using either the (unmodified) Yale method or the one by the British Geological Survey), criticality can safely be classified as non-environmental. As far as the social and economic domains are concerned, the answer is not as clear cut. Indeed market (i.e., economic) and geopolitical (i.e., socio-political) factors contribute to overall supply risk.

At the bottom line, the main question is: What does one seek to evaluate in terms of criticality in general and in the context of a LCSA specifically? In this Task, only supply risk methods have been included in the evaluation (see section 3.1). Sonderegger et al. (2020) argue that, for the time being, supply risks have only been assessed at midpoint level. When assessed at endpoint level, they suggest to evaluate "impaired product functions" and "additional costs of production".[5] This points to economic implications, suggesting to assess criticality as part of the economic sustainability pillar.

If criticality was to be evaluated as part of the economic dimension, another implication would be that the formula LCSA = environmental LCA + social LCA + LCC (Kloepffer, 2008; UNEP/SETAC LCIn, 2011) would no longer hold, given that criticality would not be expressed as costs (alone). In view of the issue that the classification is partly done because of the inventory data used (e.g. human health impacts and resource depletion assessed as part of "environmental" LCA, relying on elementary flows), Bachmann (2013) already pointed at this shortcoming: the different building blocks of this equation do not exactly match the three pillars of sustainability. As an alternative, Bachmann (2013) suggested to distinguish at impact (or AoP) level (modified): "ecosystem (nature)-related LCA" + "economic LCA" + "social LCA" (including human health impacts, too).

From a product system perspective, supply risks are outside-in risks (i.e., risks affecting an organisation/product system; inside-out risks, by contrast, originate from the organisation/product system and affect its environment). The ILCD handbook from 2010 already recommended to at least discussing inside-out risks such as accidents if those risks are considered decisive elements in a sustainability context (see provisions 9.4 in EC-JRC, 2010). Bachmann (2013) raised the question what the specific cut-off criterion in

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[5] Note that for instance Gemechu et al. (2017) emphasise supply disruption as the main issue, "geopolitical aspects" being the "constraint factor". In the EC-CA (European Commission, 2017b), the importance for the economy is emphasised.

terms of frequency or likelihood is to include or exclude a risk in LC(S)A. Beyond supply risks, only little research in the context of LCA has been conducted(see for instance Wolf (2014), though only dealing with human health related risks from accidents). However, this goes beyond the scope of the ORIENTING project.

WP2 could investigate how to incorporate/integrate criticality into the economic pillar, be it at midpoint or endpoint/AoP level. In any case, a decision needs to be made whether criticality is assessed within or outside (i.e., in parallel) the scope of the three pillars of sustainability. If it was treated in parallel, care would need to be taken which importance is assigned to it relative to environmental, economic and social impacts.

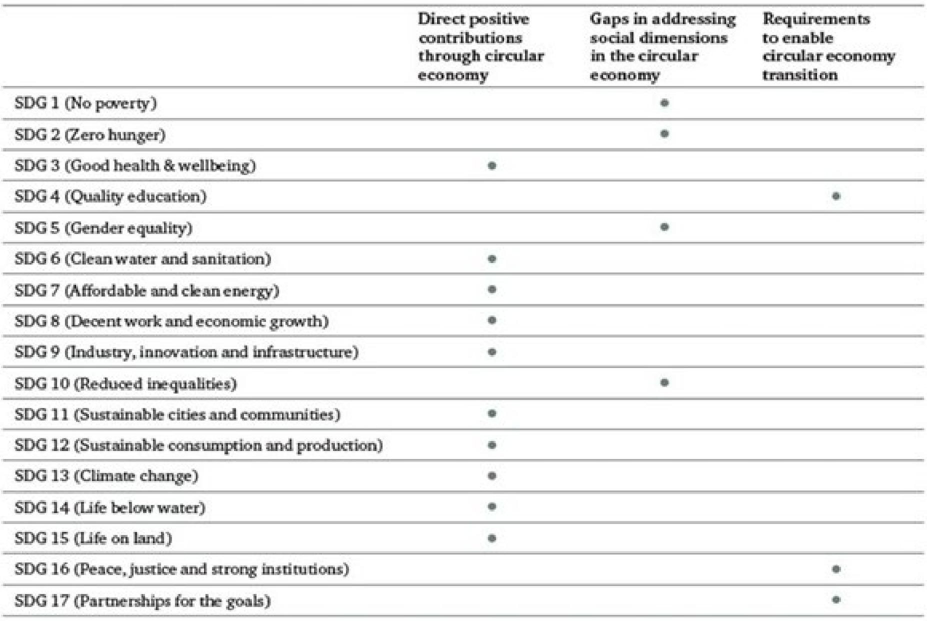
PART 2: Product-related Circularity

7 Introduction

Sustainable Development is the overarching concept in European policy development. This is as exemplified by the 17 Sustainable Development Goals (SDGs) that cover environmental, social and economic aspects (United Nations General Assembly, 2015). Circular Economy (CE) is a concept that sits within Sustainable Development and enables number of SDGs (Charter, 2018b).

At a macro level, CE is about a shift from the current linear economy based on “take-make-waste” to retaining value in economic and social systems; in circular economy, waste does not exist. The focus of CE is on a systemic shift at an economic and societal level rather than purely a focus on incremental improvements and efficiency (BSI, 2017).

The European Commission and ISO Technical Committee (TC) 323 have illustrated the linkage between CE and sustainable development with explicit references in policy documents and the current ISO TC323 WG1 working definition (see Table 8); this was missing from many earlier definitions. The linkages between CE and Sustainable Development Goals (SDGs) and gaps related to social dimensions were illustrated in a paper by Chatham House[6] (Preston et al., 2019). According to this paper, CE is more focused on economic dimensions and social dimensions are less well considered. Moreover, the paper also highlights the gaps in addressing social dimensions related to CE, showing the links to relevant SDGs as illustrated in Figure 2.



	Direct positive contributions through circular economy	Gaps in addressing social dimensions in the circular economy	Requirements to enable circular economy transition
SDG 1 (No poverty)		●	
SDG 2 (Zero hunger)		●	
SDG 3 (Good health & wellbeing)	●		
SDG 4 (Quality education)			●
SDG 5 (Gender equality)		●	
SDG 6 (Clean water and sanitation)	●		
SDG 7 (Affordable and clean energy)	●		
SDG 8 (Decent work and economic growth)	●		
SDG 9 (Industry, innovation and infrastructure)	●		
SDG 10 (Reduced inequalities)		●	
SDG 11 (Sustainable cities and communities)	●		
SDG 12 (Sustainable consumption and production)	●		
SDG 13 (Climate change)	●		
SDG 14 (Life below water)	●		
SDG 15 (Life on land)	●		
SDG 16 (Peace, justice and strong institutions)			●
SDG 17 (Partnerships for the goals)			●

Figure 2: Circular Economy in the 2030 Agenda Framework: contributions and gaps (Source: Preston et al., 2019)

The European Commission (EC) has taken global leadership on Circular Economy (CEAP 1.0) with its 1st Circular Economy Action Plan (CEAP 1.0) launched in December 2015 (European Commission, 2015) and a 2nd Circular Economy Action Plan (CEAP 2.0) published in March 2020 (European Commission, 2020a). The CEAP 2.0 has broadened the scope to cover a wider number of value chains:

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[6] Chatham House is an international affairs and policy think tank (https://www.chathamhouse.org/).

> *"Priority will be given to addressing product groups identified in the context of the value chains featuring in this Action Plan, such as electronics, ICT and textiles but also furniture and high impact intermediary products such as steel, cement and chemicals. Further product groups will be identified based on their environmental impact and circularity potential."*

In addition, a new Sustainable Products Initiative (SPI) - focused on circular economy product policy development – was included into CEAP 2.0 that is now in expert and public consultation with the goal of publication in December 2021.[7]

Circular Economy is also becoming an area of growing policy interest in G20 countries. This resulted in the launch of a number of global initiatives focused on Circular Economy e.g. Platform for Acceleration of Circular Economy (Charter & Cheng, 2021; PACE, 2021c).

There is growing interest in measurement of CE at various levels (e.g. products, organisations, regions), and several metrics and indicators are being developed. Discussion in expert interviews indicated the metrics and indicators were sometimes being used interchangeably without clear distinctions (see section 8.2). New initiatives are being established to explore measurement. For instance, a new ISO working group (WG) was founded to take forward circular measurement: ISO TC 323/WG3. Furthermore, the Circular Economy Indicators Alliance (CEIA) has been recently launched with multi-stakeholder membership including the European Commission and the European Environment Agency with the secretariat provided by PACE (PACE, 2021b). The stated aim of CEIA is to foster collaboration between governments, businesses, entrepreneurs, and experts and to take forward thinking on circularity metrics with a particular focus on different market sectors: food; electronics; textiles; electronics; plastics; and capital equipment. CEIA have published two reports focused on measurement of CE for government and business. In Europe, there is growing interest at government level e.g. Bellagio Declaration (ISPRA & EEA, 2020) and this is highlighted in a recent CEIA report on Government (PACE, 2021c). A CEIA report on Business provides an overview at a company level, although with little mention of product-related circularity issues.

Business leadership on CE measurement appears to have been taken by the World Business Council for Sustainable Development (WBCSD) and Ellen MacArthur Foundation (EMF), who have developed tools that incorporate product-related circularity metrics and indicators. To date, measurement of circularity in business seems to be more focused at the company and business unit level rather than at a product level (WBCSD, 2018). Experts interviewed in the context of this project suggested that two product-related circularity indicator/metric tools are being most used by companies: 1) Circular Transition Indicators – Version 2 (WBCSD, 2021), and 2) Circulytics (EMF, 2019) (see section 8.2). It needs to be noted that both tools are focused on the company level, i.e., not on products themselves. Details of actual usage of the tools are not in the public domain, but it is likely that use of these tools will be primarily by transnational companies that are trying to take leadership in CE/product-related circularity and/or those that are receiving more pressure from external stakeholders e.g. customers, investors and NGOs. However, the analysis provided below in this report has indicated that there has been a considerable amount of academic research and published papers related to product-related circularity indicators and metrics. This indicates a gap or "lagged effect" between the research and business communities, e.g. a number of tools and methodologies have been developed in academia but few are being used by companies due to a lack of external and internal drivers. Many companies are unlikely to be motivated to measure product-related circularity unless there are external drivers (e.g. customers, legislation, standards) or there is a strong business case (e.g. cost saving, efficiency gains) (WBCSD, 2018).

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[7] Sustainable Products Initiative (SPI) https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/12567-Sustainable-products-initiative_en

At a business level, a number of companies practice ecodesign with a focus on integrating environmental aspects into product design and development throughout the life cycle and this includes materials, energy and other considerations. Ecodesign strategies may also include, in effect, what might be defined as product circularity (or rather product-related circularity) strategies (see Table 18 in the Annex A, section 13.1.2).

It appears that some leading companies have started to highlight circularity in their ecodesign strategies (see section 13.1.2), with a focus on retaining *value* in products (e.g. through servicing and refurbishment), components (e.g. through parts harvesting) and materials (e.g. through recycling). A “Circular Ready Design” standard has been also proposed by industry within CEN/CENELEC JCT10.

Given the product (including material) focus of the ORIENTING project, CE strategies tailored to other subjects (e.g. whole economies/societies and sectors as well as corporate, business unit and process levels of organisations) are less relevant and are therefore mostly disregarded in the following sections of this document. Essentially, CE thinking at a product level focuses on maximising the *value* in products, components and materials for as long as possible in economic and social systems. The focus is therefore not on waste but about reframing the discussion over the systemic change. When considering CE within a lifecycle thinking context, “End of Life” should be considered practically as much further into the future than compared to traditional “take-make-waste” linear thinking.

For clarity, the acronym “LC(S)A” is sometimes used in this document to indicate that both, environmental LCA and LCSA may be concerned.

7.1 Definition of circular economy and other terms

The Circular Economy (CE) concept builds on multiple schools of thought, some of which date back to the 1960s, including: industrial ecology, industrial symbiosis, performance economy, biomimicry, cradle to cradle, blue economy, regenerative design and natural capitalism (BSI, 2017). However, the concept became mainstream also through to the policy attention given to it by the CEAP 1.0. More recently, the Ellen MacArthur Foundation (EMF) has played a pivotal role in raising awareness and in engaging business (EMF, 2021).

Considering the broad origin and use of the CE concept, Kirchherr et al. (2017) identified 114 circular economy definitions in different sources of literature. The findings indicated that CE is primarily highlighted in these definitions as a combination of reduce, reuse and recycle activities. The systemic shift associated with CE is often not acknowledged in the definitions as well as the explicit linkages of CE to sustainable development. The research indicated that CE meant many different things to different people. Kirchherr et al. (2017) highlighted an illustration of this through a reviewer’s comment noted that “some of the authors […] seem to have no idea about what [CE] is about” with some equating CE to recycling. The research found that there were a proliferation of CE conceptualizations and that this “circular economy babble“, constitutes a serious challenge to policy makers, business and researchers working on this topic. This mirrors the authors experience of early discussions with global participants within ISO TC 323. There is a clear need for a universal agreed definition of Circular Economy and the associated terminology (Charter & Cheng, 2021) and ISOTC323/WG1 are in the process of developing an international standard estimated to be published within the next 3 years.

In an attempt to arrive at a CE definition for ORIENTING, definitions from different sources (i.e., reviews, existing standards or standards in development) have been compiled (Table 8). Note that the CEAP 2.0 (see European Commission, 2020a) does not provide an explicit definition of CE but states that “the EU needs to accelerate the transition towards a regenerative growth model that gives back to the planet more than it takes, advance towards keeping its resource consumption within planetary boundaries, and therefore strive to reduce its consumption footprint and double its circular material use rate in the coming decade". Previously, CEAP 1.0 instead referred to "The transition to a more circular economy, where the value of products, materials and resources is maintained in the economy for as long as possible, and the generation of waste minimised, is an essential contribution to the EU's efforts to develop a sustainable, low carbon, resource efficient and competitive economy".

Table 8: Non-exhaustive list of definitions on (or descriptions of) Circular Economy or Circularity

Definition	Source
Circular economy	
an economy where wastes are recycled into resources, either through a technological feedback mechanism or through a natural ecosystem feedback mechanism, so that the stock of resources is constant or increasing over time.	Pearce and Turner (1990)
economy that is restorative and regenerative by design, and which aims to keep products, components and materials at their highest utility and value at all times, distinguishing between technical and biological cycles	BSI 8001 (2017)[8]
economic system that systemically maintains a circular flow of resources, by regenerating, retaining or adding to their value, while contributing to sustainable development Note: as the terms in the definition and the definition are meant to be broad, definition of technical cycle and biological cycle are included in subsidiary terms that relate back to the definition of circular flow of resources that are embedded in the definition	ISO TC 323/WG 1[9]
an economic model wherein planning, resourcing, procurement, production and reprocessing are designed and managed, as both process and output, to maximise ecosystem functioning and human well-being	Moraga et al. (2019)[10] (a wider definition)

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[8] It indicates the Ellen MacArthur Foundation (EMF) definition as the definition used; also defined (with the same words) in ISO 20400:2017 on "Sustainable procurement — Guidance" and ISO 14009:2020 on "Environmental management systems — Guidelines for incorporating material circulation in design and development"

[9] The WG currently develops a standard that covers the definition, terminology and framework for implementation, note that this is a working definition as at March 2021; Currently, the terms "technical cycle" and "biological cycle" are defined as in BSI 8001 (2017).

[10] *sensu latu* definition given in section 2.1.1, reproduced from Murray et al. (2017); note that Moraga et al. (2019) speak about, but do not provide a *sensu strictu* definition: "CE is distinguished from the linear economy by two characteristics: slowing and closing resource loops".

Definition	Source
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	Saidani et al. (2019), citing Kirchherr et al. (2017)
A circular economy aims to maintain the value of products, materials and resources for as long as possible by returning them into the product cycle at the end of their use, while minimising the generation of waste. The fewer products we discard, the less materials we extract, the better for our environment.	Eurostat[11], noting that this is not a proper definition. However, it emphasises the goal of a CE.
A circular economy is a systemic approach to economic development designed to benefit businesses, society, and the environment. In contrast to the “take-make-waste” linear model, a circular economy is regenerative by design and aims to gradually decouple growth from the consumption of finite resources.	EMF[12]
Circularity	
a state of a specified system, organization, product or process where resource flows and values are maintained whilst benefiting sustainable development	Working draft of ISO 59020:2021 (ISO TC 323/WG 3), note that this is a working definition as at April 2021
approach to promote the responsible and cyclical use of resources	Moraga et al. (2019) (general definition given at the beginning of the introduction)
the ability to conserve both the quantity and the quality of the material	Bracquené et al. (2020)

Confirming the findings by Kirchherr et al. (2017), the definitions vary in many respects:

1. Subject: the concerned system ranges from the economy (including “economic system”, “economic model” or “economic development”), to different levels also below the economy (i.e., micro, meso and macro scale or “specified system, organization, product or process”);
2. Only few definitions also mention specific actions that are intended to be changed; these range from “minimising the generation of waste” and “wastes are recycled into resources” to a range of production processes (“planning, resourcing, procurement, production and reprocessing” and related

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[11] https://ec.europa.eu/eurostat/web/circular-economy/overview (accessed on 14 May 2021)

[12] https://www.ellenmacarthurfoundation.org/explore/the-circular-economy-in-detail (accessed on 14 May 2021)

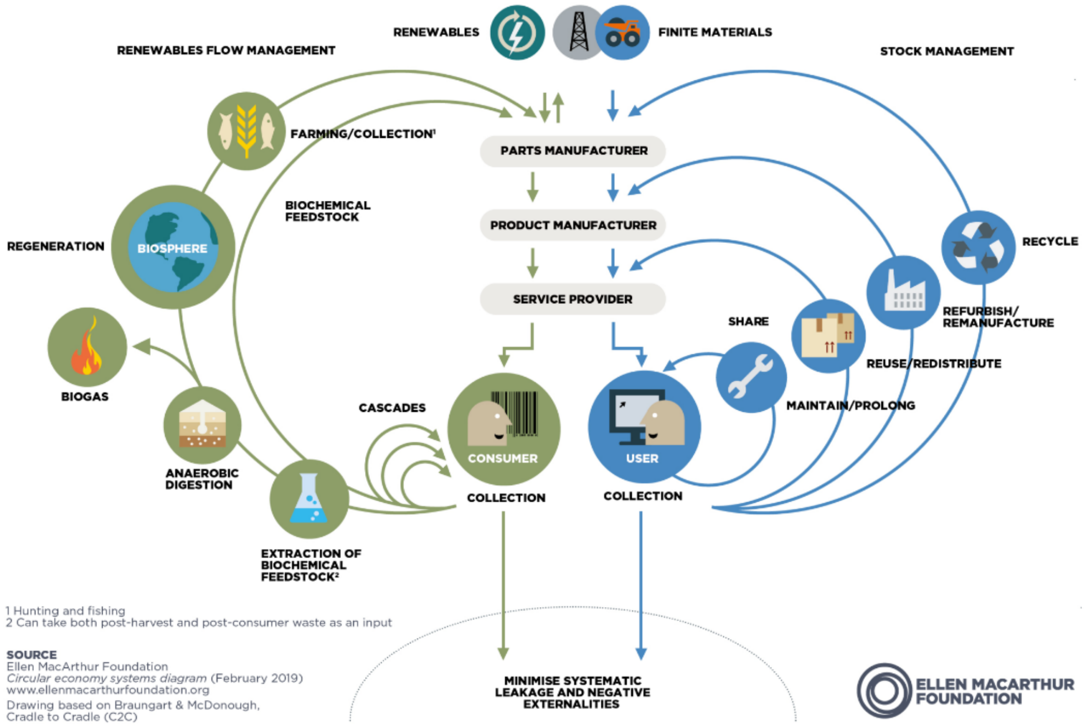
to sourcing “consumption of finite resources”), up to including consumption (“production/distribution and consumption processes”);

3. The flows to be established are described as “restorative and regenerative” (including “regenerative by design”), “maintaining resource flows”, “maintaining circular flows”, “cyclical use”, “reducing, alternatively reusing, recycling and recovering materials”, “returning [products, materials and resources] into the product cycle”. It can be noted that only the definition proposed by Kirchherr et al. (2017) and adopted by Saidani et al. (2019) explicitly refers to reducing material use. As explained in section 7.1.3, however, CE in contrast to Material Efficiency is not primarily concerned with reducing the amount of materials used in products. Especially in view to reduce the dependence on critical raw materials, the parsimony principle, i.e., use as little as necessary and possible, remains a valid measure in the context of ORIENTING;
4. The items concerned are “materials” or “products” alone or together, once also complemented with “components” or “resources”. Resources include materials, but may in addition refer to water, land or even labour. In particular, while reuse of water is promoted by the CEAP 2.0 (European Commission, 2020a), land and noticeably labour are not meant by “resources” in this context. In an early definition, “wastes” are the main focus that should become resources;
5. Quality aspects are mentioned frequently (i.e., “keep at highest utility and value”, “maintaining values”, “regenerating, retaining or adding to their value”, “maintain the value of products, materials and resources” and “conserve both the quantity and the quality”), although only two definitions also mention temporal aspects explicitly, i.e., “at all times” or “for as long as possible”;
6. Explicitly addressing the biosphere beyond the technosphere only concerns definitions from the standardisation world and few others;
7. A link to sustainable development is frequently established (i.e., “benefiting” or “contributing to sustainable development”, “maximise ecosystem functioning and human well-being”, “accomplish sustainable development, thus simultaneously creating environmental quality, economic prosperity and social equity, to the benefit of current and future generations” and “designed to benefit businesses, society, and the environment”). In the definitions relating to sustainability, it appears to be acknowledged that only those measures that contribute to sustainable development should be denoted as belonging to a circular economy, i.e., the end is sustainable development and CE measures should contribute to that.

ORIENTING seeks to develop a Life Cycle Sustainability Assessment “methodology that can assess goods produced under linear as well as circular business models” (taken from the proposal’s abstract). As a result, the LCSA methodology evaluates the degree to which a product system is sustainable. A given product system may or may not be circular and circularity may concern the product itself or parts of it (e.g. components or individual materials). Several studies have shown that “more circular” does not necessarily always mean “more sustainable” (e.g. de Oliveira et al., 2021; Dieterle et al., 2018; Helander et al., 2019; Iraldo et al., 2017). So, measures towards CE are not an end in itself but need to be evaluated against the overall goal of sustainable development. This also means that maintaining the value of materials “as long as possible” or “at all times” should be changed into “as long as justifiable from a sustainable development perspective” if reference were to be made to temporal aspects. At the same time, measures can concern different items (i.e., materials, components or the product itself) at many places in the value chain of a product (see section 7.2) such that it would be cumbersome to list them all. While the definition BSI (2017) notes that CE is a state (i.e., not an approach), circularity can be considered a concept or approach.

A final observation is that the term "product circularity" (as mentioned in ORIENTING's DoW) is not defined in the consulted literature.[13] In the end, it is the materials (or resources) contained in products (or components thereof) or used in their production processes whose use shall become more circular. This can of course also be achieved by prolonging the use of products themselves. Therefore, the term "product-related circularity" or short "circularity" will be used.

In view of these considerations and for the purpose of ORIENTING, the following definition of "circularity" is proposed: "approach to promote the extended and/or cyclical use of materials", modified from Moraga et al. (2019). "Use" in this definition includes technosphere hibernation beyond abandoned parts (i.e., materials in landfills, even though these could be sourced through urban mining), noting that distinguishing between technosphere hibernation and technosphere dissipation is arbitrary (van Oers et al., 2020). Materials can be recycled and reused through biological and technical cycles as depicted in the butterfly diagram by EMF (see Figure 3). An additional consideration is that products designed for or operating in biological system also need to consider compostability and biodegradability.



1 Hunting and fishing
2 Can take both post-harvest and post-consumer waste as an input

SOURCE
Ellen MacArthur Foundation
Circular economy systems diagram (February 2019)
www.ellenmacarthurfoundation.org
Drawing based on Braungart & McDonough, Cradle to Cradle (C2C)

Figure 3: Butterfly diagram by EMF

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[13] Product circularity could be viewed as a generic term for various product-related circularity approaches that sit within the broader approach of ecodesign for which life-cycling thinking is a key backbone. There are two recently published international ecodesign standards: IEC 62430:2019 (IEC, 2019) (dual logo standard: IEC/ISO) and ISO 14006:2020 (ISO, 2020). In both standards, the definitions read:

1. Environmentally conscious design (ECD; also referred to as ecodesign, design for the environment (DFE), green design and environmentally sustainable design): *systematic approach which considers environmental aspects in the design and development with the aim to reduce adverse environmental impacts throughout the life cycle of a product*
2. Ecodesign: *systematic approach that considers environmental aspects in design and development with the aim to reduce adverse environmental impacts throughout the life cycle of a product*

7.1.1 Activities in standardisation bodies

After discussion within the core team that developed BS8001:2017, the EMF definition was used in this standard based on feedback from UK companies that had piloted clauses of the standard. Companies stated that EMF definition was being used most commonly at that time (2016-2017) to develop their CE strategy and plans, so that a new definition was not needed. In addition, at the time of the piloting of clauses of BS8001:2017, none had developed measurement strategies (indicators and metrics) as they were still developing their understanding of what CE meant for their companies at organisational, business unit, process and product levels. The WBCSD report in 2018 indicated that the majority of the companies surveyed in their research were exploring circularity measurement at an organisational level rather than a product level (WBCSD, 2018).

International Standards Organisation (ISO) have recognised that there is increasing global interest in Circular Economy, driven by growing policy and stakeholder interest (Charter & Cheng, 2021), and have established an ISO Technical Committee (TC) ISO TC 323 with a brief to drive standards development related to CE. BS8001:2017 (UK) (BSI,2017) and CP XP X30-901 (France) (AFNOR Group, 2018) were used as the initial building blocks for new standards development within ISO TC 323. At present (June 2021), there are five standards in development under five working groups with ISO TC 323:

1. ISO/TC 323/WG1 - ISO 59004 – Circular – Economy - Terminology, principles and framework for implementation
2. ISO/TC 323/WG2 – ISO 59010 - Circular Economy – Guidance on business models and value networks
3. ISO/TC 323/WG3 – ISO 59020 - Circular Economy - Measuring circularity
4. ISO/TC 323/WG4 – ISO TR 59031 - Circular Economy – Performance-based approach for Circular Economy
5. ISO/TC 323/WG5 – ISO 59040 – Circular Economy - Product circularity data sheet

The lack clarity over a universally agreed definition and confusion over terminology is being worked on in the new standard in ISO TC323/WG1 that covers the definition, terminology and framework for implementation. Agreement of a common definition is essential to the development of the other four standards in development. See Table 8 for the current working definition of Circular Economy in WG1.

A series of online meetings are presently being undertaken within ISO TC323/WG1 amongst international experts with a view to producing a Committee Draft (CD. The goal was to tackle all expert comments in the 1st Working Draft (WD) and to produce a CD by the 31st May 2021. However, due to the complexity of the work, in May 2021, it was decided that a 2nd WD would be produced by the 31st May 2021. However, as at 8th June 2021 a 2nd WD has not been published. The CD is now targeted to be produced in Q3 or Q4 2021 and will then be sent to ISO members for voting and comments at a national level e.g. the text will move from expert comments to national comments.

As indicated above, one of the challenges associated with the development of a sister standard on Circularity Measurement (ISO TC323/WG3) is that ISO TC323/WG1 are still working on a definition at an expert level (as per below) and there has been no national comments and therefore no agreement on the definition. A matrix management approach has been created in an attempt to help manage this “parallel processing” challenge of ensuring consistency between the five standards.

7.1.2 Explicitly including technical and biological systems

The currently discussed definition by ISO TC 323/WG 1 brings in the concept of the Circular Economy having Technical Systems and Biological Systems in the terms of material flows related to products. In line with this, the Ellen MacArthur Foundation introduced the so-called “Butterfly” diagram (see Figure 3 above) that built on original thinking from McDonough & Braungart in the book Cradle to Cradle (Braungart & McDonough, 2002). This describes product systems that are built on biological nutrients (e.g. wood, cotton, primary food sources) and technical nutrients (e.g. metals, non-metallic minerals, plastics). Whist this is conceptually useful, it should be considered d that many products include mixed materials. For example, standard Healthy Sea Socks (Healthy Seas Socks, 2021) includes a mix of organic cotton (73%) (biological nutrient), elastane (2%) (technical nutrient) and regenerated 2nd life nylon (25%) from fishing gear (technical nutrient).

7.1.3 Relationship between Circular Economy with Materials Efficiency

Circular Economy (CE) is a systems level approach whereas Materials Efficiency (ME) is part of the broader concept of Resource Efficiency or even more broadly Eco-efficiency (DeSimone & Popoff, 1997). Resource efficiency is a broad umbrella term that describes efforts to reduce the total environmental impact of the consumption and production of products and services, from raw material extraction to final use and disposal. Whilst CE and the ME are sometimes referred to interchangeably, there are some distinct differences. Fundamentally, ME does not holistically re-address the linear model of consumption and production; however, it can support the development of more material efficient products/ business models and the transition towards a CE. In fact, a CE approach takes a whole systems perspective, where materials are systematically retained, restored or regenerated. It means being more effective and optimizing how materials are managed across their life cycle to reduce environmental impact. Implementing its principles in an organization might require a paradigm shift in how an organization operates. ME is concerned with the efficient use of materials, waste prevention and reduction, and causing minimal damage to the environment and depletion of natural resources. It means doing more with less and delivering greater value with less. Organizations might become more materials efficient through relatively simple, incremental actions (see Table 8).

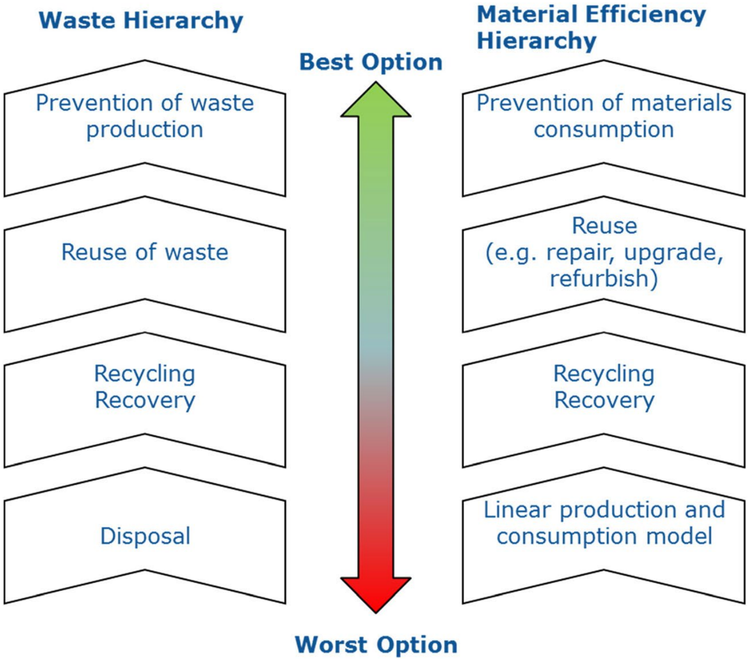

Figure 4: Relationship between waste and materials efficiency hierarchies (Source: Cordella et al., 2020)

ME strategies align to the hierarchical approach set out by the EC Waste Framework Directive (Allwood et al., 2011; Bakker et al., 2014; European Commission, 2008c, 2018a) as shown in Figure 4. The Directive presents a waste hierarchy for reducing the waste output and its disposal in landfill. Implicit in the Directive is the acceptance of waste rather than thinking of the retaining or regenerating value of value in products, components and materials that is implicit in many Circular Economy definitions (see Table 8). The waste hierarchy details a priority order for managing waste, moving from prevention of waste (the preferred option), to reuse, recycling, other forms of recovery (e.g., energy recovery), and disposal (the least preferred option). The goal is to strive for prevention over reuse, and for reuse over recovery, etc. Waste is defined in the Waste Framework Directive as "any substance or object which the holder discards or intends or is required to discard." The current definitions of prevention, reuse, recovery, and recycling all hinge on the assumption that a product at a certain point in time inevitably will become waste (see Figure 5).

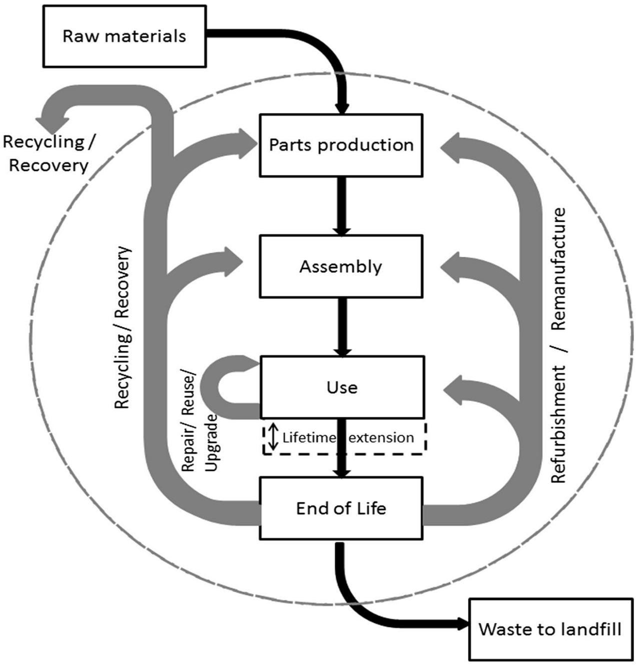

Figure 5: Material efficiency aspects in the product life cycle (Source: Cordella et al., 2020)

7.2 Circular economy strategies

As stated above, CE can be defined at various levels. This section will focus on circularity strategies that can be applied at product level. It is acknowledged that CE is a broader concept than material efficiency (see section 7.1.3).

In the context of products, circularity is fundamentally based on materials. The concept of thinking about products from the perspective of biological nutrients (materials) and technical nutrients (materials) has gained increased recognition and, as indicated in Table 8 and section 7.1.2. This is now being aligned in the ISO working definition of Circular Economy (see Table 8). However, in practice, the Butterfly diagram (see Figure 3) is a simplification of the reality of the materials mix of many products, i.e., many products include a mix of biological nutrients (materials) and technical nutrients (materials). Another key aspect that needs to be taken into account when considering material efficiency and circularity issues related to products is whether products are energy-using (e.g. consumer electronics, vehicles), energy-related (e.g. taps and showers, windows), or non energy-using products (e.g. furniture, bed mattresses). This is because material efficiency and energy efficiency measures could play a more significant or secondary role in reducing impacts of products depending on the type of product.

Within the existing product-related Implementing Measures with the EC Ecodesign Directive (European Parliament & Council, 2009) the focus so far has been mainly on reducing energy consumption and CO_2 emissions. However, with the aim of promoting a more systematic implementation of material efficiency aspects (e.g. durability, repairability, recyclability), the CEAP 1.0 (European Commission, 2015) delivered a mandate to CEN/CENELEC to publish a series of Materials Efficiency standards which have now been published (see footnote 15).

From a practical perspective in companies, exploring product circularity strategies does not happen in a vacuum. Product circularity is one aspect of ecodesign. One of the challenges of implementing ecodesign, in product design and development processes, is balancing the trade-offs between environmental aspects (e.g. energy vs. materials issues), economic costs, technical feasibility, amongst others. For example, for energy-using products, reducing energy consumption (aspects) relates to reducing carbon emissions (impacts) that also need to be balanced against materials and/or circularity considerations.

There are different classifications or hierarchies, organising measures or strategies related to CE and material efficiency (e.g. Potting et al. (2017), Moraga et al. (2019) or UNEP (2019b)). Given that ORIENTING seeks to develop a LCSA framework that considers CE aspects at a product level and aims to not to overcomplicate issues, the following hierarchy of strategies will be used[14] that has been developed for material efficiency using a 3Rs approach at the product level (Cordella et al., 2020):

1. Reduction;
2. Reuse;
3. Recycling/Recovery.

Note that the classifications and hierarchies distinguishing more Rs at the highest level can be mapped into the 3Rs as suggested here. Although functional for simplification summary purposes, the above 3Rs approach does not explicitly cover all the characteristics of product-related circularity and issues. Some of those weaknesses of the materials efficiency and within it the 3Rs approach include:

A. System level
    - Focus is sequential and linear
    - Does not take account of loops and multiple lives
    - Does not distinguish between Technical System and Biological System
B. Product level
    - Does not include options to use renewable materials
    - Does not include upcycling of products and materials
    - Does not acknowledge that some strategies are very different e.g. refurbishment and remanufacturing

In the following, the 3Rs and definitions found in two standards are presented one after the other. The two standards are “Framework for implementing the principles of the circular economy in organizations – Guide” (BS8001:2017) (BSI, 2017) and “Definitions related to material efficiency” (PD CLC/TR 45550:2020) (CEN, 2020) the latter of which relates to series of specific material efficiency standards related to Energy-related Products

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[14] Note that during the identification of relevant literature, the 9Rs concept by Potting et al. (2017) has nevertheless been used (see section 8.1).

(ErPs) that fall under the scope of the EC Ecodesign Directive.[15] Note that some of the definitions refer to further terms defined in those standards that are to a large extent also provided.

7.2.1 Reduction

The first of the 3Rs concerns reduction, i.e., direct reduction of the quantity of materials used for products and services. According to Allwood et al. (2011), this could be addressed in product (eco)design and development through for example by :

- Dematerialisation, defined by BSI (2017) as "delivery of a function with no or reduced requirement for materials, often by a move from a physical to a digital alternative";
- Reducing materials use;
- Avoidance of over-specifications;
- Light-weighting.

Within a company's ecodesign process, a designer may decide to reduce the overall weight of a product and/or reduce the number of materials used in the product (see Annex A, section 13.1). These measures occur during a life cycle stage that is commonly not distinguished in LC(S)A, i.e., the product development stage. Note that in this document the use of recycled materials is addressed in the third category (see section 7.2.3).

7.2.2 Reuse

The second of the 3Rs is reuse which is understood broadly as to mean prolonging the use of products, or parts of products (Bakker et al., 2014). This could be addressed in design and development through (Allwood et al., 2011):

- Increased durability (Alfieri et al. 2018a; 2018b), see also the definitions of "durability" in Table 9;
- "Facilitating repair, reuse and upgrade (RRU)" operations (Cordella et al., 2018), see also the definitions of "repair", "reuse" and "upgrade" in Table 9;
- Refurbishment and remanufacturing processes (Russell, 2018), see also the definitions of "refurbish" and "remanufacturing" in Table 9.

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[15] The specific standards are:
- EN 45552:2020: general method for the assessment of the durability of energy-related products (relevant definitions highlighted below)
- EN 45553:2020: General method for the assessment of the ability to remanufacture energy-related products (relevant definitions highlighted below)
- EN 45554:2020: General methods for the assessment of the ability to repair, reuse and upgrade energy-related products (relevant definitions highlighted below)
- EN 45555:2019: General methods for assessing the recyclability and recoverability of energy-related products (relevant definitions highlighted below)
- EN 45556:2019: General method for assessing the proportion of reused components in energy-related products (relates to components rather than products therefore definitions not highlighted below)
- EN 45557:2020: General method for assessing the proportion of recycled material content in energy-related products (relates to recycled material content rather than products therefore definitions not highlighted below)
- EN 45558:2019: General method to declare the use of critical raw materials in energy-related products (relates to critical raw materials rather than products therefore definitions not highlighted below)
- EN 45559:2019: Terms and definitions related to the methods for providing information relating to material efficiency aspects of energy-related products (no definitions highlighted)

While these measures again occur during the product development stage, the implications appear during the use stage (including maintenance) and the End of Life of the product stage, commonly assessed in LC(S)A.

Table 9: Terms related to the second of the 3Rs (i.e., reuse) defined in BS8001:2017 (BSI, 2017) or PD CLC/TR 45550:2020 (CEN, 2020)

Term	**BS8001:2017**	**PD CLC/TR 45550:2020**
Closed loop system	2.32.1 closed loop system system in which products, components or materials are reused or recycled by an organization or a co-operating group of organizations into the same or similar products, components or materials with minimal loss of quantity, quality or function	Not defined
Dematerialisation	2.19 dematerialization delivery of a function with no or reduced requirement for materials, often by a move from a physical to a digital alternative	Not defined
Disassembly	2.20 disassembly non-destructive taking apart of an assembled product into constituent materials and/or components	4.3.2 disassembly process whereby a product is taken apart in such a way that it could subsequently be assembled and made operational
Durability	2.23 durability maximum potential lifetime of a product, component or material to perform a required function under intended conditions of use and maintenance for a long period of time before it becomes obsolete because it can no longer be repaired and/or upgraded	4.2.1.1 durability <of a part or a product> ability to function as required, under defined conditions of use, maintenance and repair, until a limiting state is reached
Maintenance	Not defined	4.2.3.4 maintenance action carried out to retain a product in a condition where it is able to function as required
Open loop system	2.32.2 open loop system system in which products, components or materials are reused or recycled (which can be cascaded) generally amongst	Not defined

Term	BS8001:2017	PD CLC/TR 45550:2020
	unspecified organizations into alternative products, components or materials	
Reclamation/ Reclaiming	2.49 reclamation/reclaiming collection of products, components or materials with the intention of avoiding waste and with the purpose of reuse or recycling	Not defined
Recondition	2.50 recondition return of a used product to a satisfactory working condition by rebuilding or repairing major components that are close to failure, even where there are no reported or apparent faults in those components	Not defined
Refurbish	2.54 refurbish aesthetic improvement of a product, component or material, which might involve making it look like new, with no or limited functionality improvements	Not defined
Remanufacturing	2.55 remanufacture return a used product to at least its original performance with a warranty that is equivalent to or better than that of the newly manufactured product	4.3.1 remanufacturing industrial process which produces a product from used products or used parts where at least one change is made which influences the safety, original performance, purpose or type of the product
Repair	2.56 repair returning a faulty or broken product, component or material back to a usable state	4.4.4 repair process of returning a faulty product to a condition where it can fulfil its intended use
Reprocessing	Not defined	4.3.3 reprocessing restoration or modification of the functionality of a product or part
Repurpose	2.57 repurpose	Not defined

Term	BS8001:2017	PD CLC/TR 45550:2020
	using a product, its components or materials in a role that they were not originally designed to perform	
Reuse/reused	2.59 reuse/reused operation by which a product, component or material can be used again without requiring any reprocessing or treatment	4.4.3 reuse process by which a product or its parts, having reached the end of their first use, are used for the same purpose for which they were conceived
Upgradable/ upgrade	2.76 upgradable characteristic of a product that allows its physical or virtual components or parts to be separately enhanced or replaced without having to replace the entire product	4.4.5 upgrade process of enhancing the functionality, performance, capacity or aesthetics of a product
Upcycle/ upcycling	2.75 upcycle/upcycling process of converting secondary raw materials/by-products into new materials, components or products of better quality, improved functionality and/or a higher value	Not defined

Putting more emphasis on creating value through what is otherwise might be termed reuse, upcycling means that a new product is created out of a previous product or material that is no longer used in its original form (see Table 10). One example is making bags out of used fire hoses. Upcycling differs from downcycling in that the quality of the products (or materials) are retained or increased, i.e., not downgraded. Given that the two products do neither provide the same functionality nor provide their functions simultaneously (issue of multi-functionality), two different ways how to deal with up-cycling in LCA are conceivable:

a. Treating them as two separate life cycles (implying to allocate end-of-life burdens and credits between products 1 and 2).
b. System expansion (as for multi-functionality).

Table 10: Examples of upcycled products

Company	1st function	2nd function	Notes
Elvis & Kresse[16]	Fire hoses	Bags	Sold to high end retail
Freitag[17]	Tarpaulins	Bags	Modern Day Design Classic – displayed in Museum of Modern Art in New York, US
Various[18]	Fishing gear	Various	Small volume products being produced
Cycle of Good[19]	Inner tubes from tyres	Wash Bags	Examples started to emerge in the 90s

7.2.3 Recycling/recovery

As a last option of the 3Rs, the residual value of products and materials can be recovered at the "End of Life" through recycling and recovery processes (see also the definitions of "recycling" and "recovery" in Table 11). This can be addressed in design and development through the consideration of interventions such as:

- Mechanical recycling (e.g. that produces of recycled plastic pellets for materials reuse);
- Chemical recycling (e.g. production of 2nd life nylon fibres from fishing gear (Econyl, Aquafil) for materials reuse).

These measures occur at the End-of-Life of a product, i.e., a life cycle stage that is commonly distinguished in LC(S)As.

Table 11: Terms related to the third of the 3Rs (i.e., recycling/recovery) defined in BS8001:2017 (BSI, 2017) or PD CLC/TR 45550:2020 (CEN, 2020)

Term	BS8001:2017	PD CLC/TR 45550:2020
Downcycle/ downcycling	2.22 downcycle/downcycling process of converting secondary raw materials/by-products into new materials, components or products, typically of lesser quality, reduced functionality and/or lower value compared to their original intended purpose	Not defined

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[16] https://www.elvisandkresse.com/
[17] https://www.freitag.ch/en
[18] See report covering products from waste fishing gear on http://www.cfsd.org.uk/reports
[19] http://www.cycleofgood.com

Material Recovery	Not defined	4.5.4 material recovery recovery operation of any kind, other than energy recovery and the reprocessing into materials that are to be used as fuels or other means to generate energy
Recovery	2.51 recovery activity where the principal objective is to ensure that the used products, components or materials serve a useful purpose by replacing other new products, components or materials which would have had to be used for that purpose, or being prepared to fulfil that purpose, in the plant or in the wider economy	4.5.3 recovery operation of any kind, the principal result of which is waste serving a useful purpose by replacing other materials which would otherwise have been used to fulfil a particular function, or waste being prepared to fulfil that function, in the plant or in the wider economy
Recycling	2.52 recycle/recycling action of processing a discarded or used product, component or material for use in a future product, component or material	4.5.6 recycling recovery operation of any kind, by which waste materials are reprocessed into products, materials or substances whether for the original or other purposes excluding energy recovery

7.3 Different approaches to classify circular economy indicators

Circular economy indicators can be considered quite a heterogeneous group of indicators. This is due to several reasons and the lack of a common definition (see section 7.1*)* or the difficulty of arriving at one may be one of them. Nonetheless, a few authors have attempted to cluster the circular economy indicators, using different approaches. In this subsection, three approaches of clustering circular economy indicators are further discussed.

In Moraga et al. (2019), two main criteria are used to cluster the indicators, i.e., (A) what to measure and (B) how to measure. These two criteria are further divided into three pathways, i.e., (A1) by CE strategy, (A2) by measurement type, (A3) by CE definition, and (B1) by scope (0, 1, and 2), (B2) by implementation scale, and (B3) by equation type. Therefore, the authors propose six ways of clustering the different CE indicators.

Saidani et al. (2019) suggest 10 categories to classify, differentiate and orient the use of proper CE indicators. Categories from #1 to #4 are specific to the CE paradigm (levels, loops, performance, perspective). Categories #5 to #6 (usages and transversality) are related to the particular usages and fields of application of these CE indicators. Categories #7 and #8 (dimension and units) are linked to the basic features of indicators. Category #9 (format) is dedicated to the assessment framework associated to each CE indicator, facilitating for instance its computation. Category #10 (sources) specifies the background in which each CE indicator has been developed.

Based on a survey of 39 global companies and other stakeholder interviews, WBCSD (2018) classified CE indicators (or metrics as they call them) according to scope (i.e., which environmental aspects in ISO language they address: materials, water and/or energy), level, and value chain or life cycle factors (e.g. internal operations or processes of a business, or the End of Life phases of the life cycle). In contrast to Kirchherr et al. (2017) and Saidani et al. (2019) who distinguish between micro level (products, companies, consumers), meso level (eco-industrial parks) and macro level (city, region, nation and beyond), WBCSD (2018) (and de Oliveira et al. (2021)) isolate products as a separate nano-level below the micro-level. Moraga et al. (2019) also distinguish between micro, meso and macro level which they refer to as "scale" but note that the distinction is "neither consistently used nor clearly defined".

The literature review (see section 8.1) was particularly guided by the level for which a CE indicator is defined.

7.4 Goal and scope of the deliverable on product-related circularity

In ORIENTING, CE aspects are intended to be embedded in the overall analysis of environmental, social and economic impacts (LCA, Social LCA and LCC) and provide stand-alone circularity indicators. However, the scope of this deliverable is more limited to the latter. The goal of the deliverable part of product-related circularity is 1) to identify relevant approaches, concepts, methods and indicators related to circularity of products to be integrated into ORIENTING's LCSA framework (see sections 8.1 and 8.2), 2) to conduct a critical evaluation of a selection of the most promising indicators for use in LCSA on the basis of the criteria developed in T1.1 (according to section 8.3 and presented in chapter 10). This critical evaluation will result in 3) recommendations for methodological developments in WP2 (presented in chapter 11). Chapter 9 addresses specific topics of relevance.

The scope of the deliverable is limited to product-related circularity, meaning that circularity assessments at larger geographical levels, such as nations, regions, provinces and cities are out of scope. Circularity assessments for entire organizations or companies are not the main focus of this deliverable either. Circularity assessments of multiple products from one company could, however, provide useful information in this respect. Material (and component) circularity is considered to be a part of the scope of a product-related circularity assessment; the latter (product-related circularity) being broader in scope than the former (material circularity) by also including life cycle stages such as use, maintenance, repair, etc. The product-related circularity, in principle also includes (implicitly) a number of materials-related considerations or strategies within ecodesign, despite it being frequently disregarded in LCA (van Loon et al., 2021).

8 Research methodology

This section presents the methodological steps followed for the analysis of product-related circularity aspects and methods. The methodology is composed of three main steps. First, a systematic literature review was performed in order to identify the existing circularity indicators in the scientific literature and grey literature (section 8.1). These are filtered according to the scope of the project (as explained in section 7.4). The literature review was further supported by interviews with CE experts to establish the most commonly used and relevant indicators (section 8.2). Finally, the screened indicators were evaluated according to the criteria proposed by Task 1.1, already described in section 3.2 and adapted here to the specificities of the CE context (see section 8.3).

8.1 Literature review

Considering the very prolific production of documents in the field of CE and circularity, the approach taken was to identify the literature cited in or citing at least one of two recent review papers of high quality, i.e., Moraga et al. (2019) and Saidani et al. (2019). Citing literature was considered that was published until 5 March 2021.

The screening of the literature cited in Moraga et al. (2019) and Saidani et al. (2019) considered the following criteria. The methods/indicators must quantitatively evaluate products (see section 7.3). They must be workable for several product groups/sectors (not only one kind of product) and for any geography. It is acknowledged that methods addressing individual CE strategies can also be valuable when combined with others (without overlap). However, this was not considered at this stage of the ORIENTING project. A total of 25 potentially interesting methods was identified.

With respect to the literature citing Moraga et al. (2019) and/or Saidani et al. (2019), 204 publications were found. Given that the interest was to identify new methodological advances or developments, the titles and abstracts were screened to check the presence of the terms “metric” or “indicat*” and methodological developments. This reduced the number of documents to 93.

Despite the applied selection criteria, both literature searches resulted in too many items. To further narrow down the number of publications, the following procedure was adopted to identify the methods or publications for further analysis against the criteria from T1.1. Two groups were distinguished.

The methods/indicators to be evaluated against the T1.1 criteria need to fulfil each of the following criteria:

- They must be product level indicators: it needs to be noted that this criterion cannot be evaluated without ambiguity given that materials are part of products. This complies to micro-level indicators as used for instance by Moraga et al. (2019) and Saidani et al. (2019)[20];
- They must be applicable to any product (not specific to one type of product) and
- They must cover more than 1 CE strategy out of the following list of 9Rs: refuse, rethink, reduce, reuse, repair, refurbish, remanufacture, repurpose, recycle, recover (see Potting et al., 2017).

Through this, nine publications were identified that were analysed against the T1.1 criteria, presented in section 8.3:

1. Product-Level Circularity Metric (PLCM, C-metric) (Linder et al., 2017, 2020),
2. Material Circularity Indicator (MCI) (EMF & Granta, 2019),
3. Longevity indicator (Franklin-Johnson et al., 2016),
4. Circular Footprint Formula (CFF) (Zampori & Pant, 2019),
5. Product Circularity Indicator (PCI) (Bracquené et al., 2020),
6. Circularity index Circ(T) (Pauliuk et al., 2017),
7. Value-based resource efficiency (VRE) method (Di Maio et al., 2017),
8. Sustainable Circular Index (SCI) (Azevedo et al., 2017),
9. In-use occupation ratio (UOR) and final retention in society (FRS) (Moraga et al., (2021).

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[20] It needs to be noted that the categorisation into micro/meso/macro is not aligned between Moraga et al. (2019) and Saidani et al. (2019). For example, some meso level indicators labelled by Saidani et al. (2019) are not labelled as meso by Moraga et al. (2019).

Note that this prioritisation already anticipated the evaluation of five of the T1.1 sub-criteria, namely:

1. III "Source (reference)", i.e., only including methods published until 5 March 2021,
2. VII "Qualitative/Quantitative", i.e., only including quantitative methods,
3. 1.2 "Acceptance by Industry", i.e., only including methods applicable to products; note that as part of this sub-criterion the following question is to be answered: "Is the method/methodology/tool suitable for different industries, processes, products, materials or components?";
4. 5.2 "Ability to be applied to specific contexts", i.e., only including methods applicable to products, but excluding methods that considered one CE strategy only, and
5. 5.3 "Ability to be applied in unspecific contexts (generalization)", i.e., excluding methods/indicators that were specific to a given product or material.

In addition to this search, further relevant literature was identified though expert interviews (see section 8.2).

8.2 Expert interviews

Interviews were completed by 4th and 11th March 2021 with 5 experts in the field of CE and LCA:

1. Hans Kroder – ISO TC323 WG3 Convenor (leading ISO standard on measuring circularity)
2. Brendon Edgerton – World Business Council for Sustainable Development (WBCSD) (managing CE metrics team and development of CE metrics tool)
3. Patrick Schroder – Chatham House (expert actively involved in leading-edge CE thinking)
4. Peder Jensen – European Environment Agency (EEA) (leading EEA activities on measuring CE)
5. Dr. Louis Brimacombe – ex Tata Steel (LCA expert with experience of Social LCA and CE)

The experts from EEA, WBCSD and the Convenor of WG3 of ISO TC 323 (focused on the measurement of circularity) indicated that there are three product-related circularity tools that appear to be in most use and each include a series of indicators and metrics. This includes a recently updated version 2 of a tool from WBCSD and tools from Ellen MacArthur Foundation (EMF):

- WBCSD Circular Transition Indicators version 2.0 (CTI2.0), launched March 2021; version 1.0 had been published in January 2020 (WBCSD, 2020).
- EMF Material Circularity Indicator tool (EMF & Granta, 2019).
- EMF Circulytics (EMF, 2019); note that it is unclear to what extent EMF Circulytics tool has superseded the use of EMF Material Circularity Indicator tool in companies.

It can be noticed that both tools, i.e., CTI2.0 (WBCSD, 2020) and Circulytics (EMF, 2019), focus on companies, but may provide product-specific indicators as well.

The WBCSD Circular Transition Indicators version 2.0 (CTI2.0, was launched February 2021) (WBCSD, 2021) and built on version 1. CTI2.0 is an open access methodology (document) with the complementary CTI tool and with no vetting of users by WBCSD; in addition, there appears to be a more elaborate professional CTI tool available that is available for a fee. The methodology can be used across multiple sectors and different stages of the value chain. It can be applied from the product level, up to the company level. The methodology appears to have been developed with substantial piloting and testing with companies. There are a series of metrics and indicators that are used but these need further research.

The ethos behind the development of WBCSD CTI2.0 was to be:

- ➢ Objective
- ➢ Simple

- Consistent
- Material agnostic e.g. “there is no value judgement that one material is better than another”

A key part of the improvement of version 1 to version 2 was an upgrading of the content related to products for the biological system. New indicators on water circularity and CTI revenue were also included in CTI2.0. All updates to the methodology are reflected in the CTI tool.

As indicated above, there were indications that there has been significant engagement by WBCSD with companies in the development of CTI1.0 and CTI2.0. However, given the open-access nature of CTI, it is unclear the number of companies using the CTI2.0 methodology and CTI Tool and the extent that usage goes beyond WBCSD member companies.

The use of EMF Circulytics tool appears to require a screening by EMF (i.e., a selection process must be passed before the use of the tool is allowed). The type of screening process that is used and the number of companies that are using the tool are unclear.

8.3 Evaluation of prioritised circularity methods/tools against criteria provided by T1.1

A general description of the T1.1 criteria is provided in section 3.2.1. For the purpose of assessing circularity methods, the list of criteria from T1.1 has been adjusted in several ways, including regarding the way in which some sub-criteria have been interpreted to be evaluated.

Sub-criteria 1.1 “Acceptance by Policy-makers” and 3.1 “Traceability of the modelling data and model used” have been adjusted for circularity, in the same way as for criticality, as described in the changes performed within the context of task 1.5 (see section 3.2.2).

Regarding the changes related to circularity only, the scoring has been changed twice. This concerns sub-criterion 6.1b “Takes into account the life cycle thinking/approach” whose levels were adjusted to Table 12.

Table 12: Adjustments of level descriptions for sub-criterion 6.1b “Takes into account the life cycle thinking/approach” for circularity only

Score for 6.1b	Original description proposed by T1.1	Final description as used here
A	environmental, economic, and/or social concerns are assessed along their cause-effect chain following a life cycle thinking (LCT) approach	CE strategies are assessed taking a full LCT approach in terms of LC stages
B	-	-
C	only technical/physical consideration of CE measures/strategies while taking a full or partial LCT approach	CE strategies are assessed taking a partial LCT approach in terms of LC stages,
D	-	CE strategies are assessed taking a (full or partial) LCT approach in terms of LC stages, but also assessing environmental, economic, and/or social concerns beyond CE (risk of double-counting)
E	only technical/physical consideration of CE measures/strategies without taking a LCT approach (i.e., limited to one life cycle stage)	CE strategies are assessed by only looking at one LC stage

The second sub-criterion whose scoring has been changed (i.e., 5.2 “Ability to be applied to site specific contexts”) was also renamed slightly. Referring to site specificity was deemed too limiting. Rather, the evaluation should concern specificity in terms of product and/or sector as well. It is noted however that with service contracts, one could know which process (at which site) is involved. So, an aggregate information is not necessarily better. The changed name is “Ability to be applied to specific contexts” with the levels as shown in Table 13.

Table 13: Adjustments of level descriptions for sub-criterion 5.2 “Ability to be applied to specific contexts” specifically for circularity

Score for 5.2	**Original description proposed by T1.1**	**Final description as used here**
A	Yes, the method/methodology/tool can be applied to site-specific contexts	Yes, the method/methodology/tool can be applied to specific contexts
B	-	
C	Yes, the method/methodology/tool can be applied to site-specific contexts if site specific information is made available (have to be collected)	Yes, the method/methodology/tool can be applied to context-specific contexts if context-specific information is made available (have to be collected)
D	-	
E	No, the method/methodology/tool includes generic models only	(same as original proposal)

In addition to the clarification of 5.2 (see above), the way in which sub-criterion XII “Integration procedure” shall be interpreted has been clarified. The question had been raised what shall be understood by “single score” for CE methods. It was agreed to ask the following question: If the methodology provides several indicators, does it also provide a way how to integrate these indicators (e.g. into an index)? So, whether or not the developers of the method/methodology/tool only communicate/discuss the integrated result.

Three sub-criteria have been abandoned (i.e., not considered for circularity methods):

- 2.4 “Interoperability”: The question arose whether this sub-criterion can be evaluated when no tool is provided. It was agreed to put “N/A” for all CE methods because user-created spreadsheet models could be linked, but a link to LCA software is not common practice for CE right now. Note that the original idea behind this sub-criterion was whether a method or database used in one LCA software can be used in another LCA software.
- 5.1 “Inclusion of positive and negative impacts”: Given that all CE methods reward more circular and punish more linear models, all methods would have to be evaluated in the same way.
- 5.4 “Degree to which the method/methodology/tool addresses circular economy strategies”: Given that a preselection of methods had been made (see above), indicators that are too specific in terms of assessing Rs had been excluded already.

9 Analysis of specific topics

9.1 Current discussions regarding ISO/WD 59020:2021 on “Circular Economy — Measuring and assessing circularity”

At present (June 2021), a first Working Draft (WD) of ISO 59020 on “Circular Economy — Measuring and assessing circularity” was drafted by international experts from 83 countries within an editorial group of ISO

TC323/WG3[21]. This document specifies a framework for organizations in measuring and assessing circularity, whilst aiming to contribute to sustainable development.

The framework is based on a broad perspective of circularity and sustainability.

The framework is applicable to multiple levels of an economic system, ranging from national and regional, individual and groups of organizations and to products.

At present, the document lacks details on measurement, metrics and indicators at a product level.

The framework provides guidance to assess the circularity performance of an economic system and circularity strategies by measuring material and resource use and other resources using circularity indicators. The purpose is to assist organizations with performance assessment information to create circular flows whilst adding, retaining and/or regenerating resource value.

The framework takes into consideration social, environmental and economic impacts when assessing the circularity performance by building bridges to complementary methods. In the Introduction to WD it is stated:

> *"This document provides guidance for robust measurement of key information and data to assess the circularity performance of circularity strategies and the economic system. This is done by using that information and data with appropriate complementary methods and expressing that assessment as a qualitative and/or qualitative circularity performance. It incorporates an integrated view of circularity and sustainable development and is intended to be used to support the transition towards a global circular economy. The assessment will include social and environmental impacts of the circularity strategy and economic system to contribute to the UN Agenda 2030 on Sustainable Development and the Sustainable Development Goals. The measurement and assessment are based on the use of relevant and appropriate circularity indicators and indicator systems."*

In the Scope, there is the *complementary methods* that include Life Cycle Thinking (LCT)

> *"The framework is based on a broad perspective of circularity and can include other complementary approaches, such as Life Cycle Thinking, value-driven maintenance of resources."*

This is further elaborated in Annex A of the working draft.

However, as stated in the introduction ("… to assess the circularity performance of circularity strategies and the economic system"), the ORIENTING project partly overlaps with ISO TC323/WG3 given that the project aims to integrate product circularity considerations into an operational LCSA methodology. ISO TC323/WG3 cites the importance of the life cycle thinking perspective, but its scope is broader than is LCSA. The ORIENTING team should establish two-way communication with WG3 to feedback into the development of the standard.

9.2 Products covered in circularity assessments

A systematic review on the product types (or application sectors) covered in circularity assessments is lacking so far. While some CE indicators are developed in a generic way for a broad applicability (for example the Product Circularity Indicator by Bracquené et al. (2020)), other CE indicators are specifically tailored to a certain application (for example the (Predictive) Building Circularity Indicator by Cottafava and Ritzen (2021)).

Saidani et al. (2019) identified that only 3 out of 20 CE indicators at the micro level (~product level) reviewed were designed for a specific application sector. However, given the recent development of many indicators at

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[21] Published in March 2021 with comments requested from other international experts from outside the editorial group.

the micro level, even the indicators that claim to be generically applicable were yet only applied to one specific sector or product (Saidani et al., 2019).

Table 14 presents examples of recent publications on CE assessments identified during the general literature review that might be of interest for ORIENTING's demonstration cases (WP 4). Because of their limited application (see section 8.1), these were not further investigated.

Table 14: Non-exhaustive list of recent publications on CE assessments of subjects investigated in ORIENTING's demonstration cases

Topic	References
Food (without packaging)	• Amicarelli, V., & Bux, C. (2020). Food waste measurement toward a fair, healthy and environmental-friendly food system: a critical review. British Food Journal. doi:10.1108/BFJ-07-2020-0658 • Rabadán, A., Triguero, Á., & Gonzalez-Moreno, Á. (2020). Cooperation as the secret ingredient in the recipe to foster internal technological eco-innovation in the agri-food industry. International Journal of Environmental Research and Public Health, 17(7). doi:10.3390/ijerph17072588 • Saidani, M. et al. (2020). Assessing the environmental and economic sustainability of autonomous systems: A case study in the agricultural industry. Paper presented at the Procedia CIRP.
Textile (wool)	• Rossi, E., Bertassini, A. C., Ferreira, C. D. S., Neves do Amaral, W. A., & Ometto, A. R. (2020). Circular economy indicators for organizations considering sustainability and business models: Plastic, textile and electro-electronic cases. Journal of Cleaner Production, 247. doi:10.1016/j.jclepro.2019.119137 • Saha, K., Dey, P. K., & Papagiannaki, E. (2021). Implementing circular economy in the textile and clothing industry. Business Strategy and the Environment. doi:10.1002/bse.2670
Polymer-coated board	Nothing encountered during the literature review
Painting	Nothing encountered during the literature review
Concrete (or buildings in general)	• Antonini, E., Boeri, A., Lauria, M., & Giglio, F. (2020). Reversibility and durability as potential indicators for circular building technologies. Sustainability (Switzerland), 12(18). doi:10.3390/su12187659 • Calabi-Floody, A., Letelier, V., Valdes, G., & Sanchez-Alonso, E. (2020). Promoting the Circular Economy of Concrete Through Innovation in Asphalt Pavements. Paper presented at the IOP Conference Series: Earth and Environmental Science. • Cottafava and Ritzen (2021). Circularity indicator for residential buildings: Addressing the gap between embodied impacts and design aspects. Resource, Conservation & Recycling. 164, 105120. doi:10.1016/j.resconrec.2020.105120 • Finch, G., Marriage, G., Pelosi, A., & Gjerde, M. (2021). Building envelope systems for the circular economy; Evaluation parameters, current performance and key challenges. Sustainable Cities and Society, 64. doi:10.1016/j.scs.2020.102561 • Foster, G., Kreinin, H., & Stagl, S. (2020). The future of circular environmental impact indicators for cultural heritage buildings in Europe. Environmental Sciences Europe, 32(1). doi:10.1186/s12302-020-00411-9 • Heisel, F., & Rau-Oberhuber, S. (2020). Calculation and evaluation of circularity indicators for the built environment using the case studies of UMAR and

Topic	References
	Madaster. Journal of Cleaner Production, 243. doi:10.1016/j.jclepro.2019.118482 • Mirzaie, S., Thuring, M., Allacker, K., 2020. End-of-life modelling of buildings to support more informed decisions towards achieving circular economy targets. The International Journal of Life Cycle Assessment 25(11) 2122-2139. https://doi.org/10.1007/s11367-020-01807-8.

9.3 LCSA and circular economy strategies/business models

As presented in section 7.2, the CE strategies are usually represented by the three key concept groups related to material efficiency - *reduction, reuse, and recycling/recovery* – which can be further detailed in more strategic groups – *refuse, rethink, reduce, reuse, repair, refurbish, remanufacture, repurpose, recycle and recover*. The choice of representation of the strategies is a matter of taxonomy, and there is no consensus whether one is better than the other since they have a common ground. Saidani et al. (2019), for example, have analysed the coverage of CE strategies by indicators according to the differentiation of 3 groups while Moraga et al (2019) and de Oliveira et al. (2021) proposed grouping the strategies into 6 and 4 groups, respectively, adapted to the life cycle perspective and the elements from life cycle studies.

In Saidani et al. (2019), the evaluation of indicators at a micro-level (organisation, products, and consumers) included 20 indicators. From these, 9 address *maintenance* strategies, 13 include measurement of *reuse and remanufacture* strategies, 18 include *recycling* strategies measurement, and 9 of them address all of these strategy groups. However, these indicators were not analysed by Saidani et al. (2019) from the life cycle perspective (i.e., distinguish product systems, functionality and/or life cycle stages). Oliveira et al (2021) have analysed indicators measuring strategies used at a product, component or material level (58 indicators in total) according to which of the life cycle stages. Their analysis showed that

- 43% of the indicators evaluated cover strategies in *all the life cycle stages*;
- 3% only address strategies for *reduction of extraction* of natural resources (energy and materials);
- 21% target the *design/manufacturing process* strategies, however, 3% are exclusively dedicated to these strategies;
- 14% evaluate effects of strategies regarding *the acceptance and behavioural shift of consumers* in the use phase, but they are always linked to other strategies; and
- 29% of the indicators are *exclusively* dedicated to evaluating the *recovery of waste, materials and energy* in the EoL phase, but is included in 52% of the indicators.

Moraga et al. (2019) classified CE indicators according to six groups of CE strategies depending on what they seek to preserve (5 groups), or whether they seek to benchmark activities against a reference scenario (1 additional group). Strategies in group 1 aim to preserve the *function* of products or services (i.e., promote product redundancy and multifunctionality); strategies in group 2 aim to preserve the *product* (i.e., promote durability, reuse, restore, refurbish, and remanufacture); strategies in group 3, *components* (i.e., promote reuse, recovery and repurposing); strategies in group 4, *materials* (i.e., promote recycling which may also lead to downcycling); strategies in group 5, the *embodied energy*[22] (i.e., promote energy recovery); in group 6, represent a reference scenario with linear economy and no strategy. In their analysis of micro-level indicators,

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[22] Moraga et al. (2019) speak of “preserving embodied energy“. Note that this is somewhat ill-phrased because energy is always preserved. However, through incineration and capturing gases at landfills one can convert the embodied energy into useful energy.

Moraga et al (2019) found that most indicators address strategies in group 4, i.e., assessing the preservation of materials, and that recycling is the most frequently promoted strategy.

Although these studies do not use the same classification and therefore cannot be compared, they are complementary and express a common result. The reviews show that most of the indicators measure the implementation of strategies at the end of life of the products and are mainly focused on recycling. This finding could mean that recycling has been so far the main focus among companies and experts and that there are not sufficient literature and/or data for other strategies that should be prioritised.

Table 15 shows the CE strategies covered by the indicators analysed in this deliverable (see sections 8.1 and 10). Because the classifications by Moraga et al. (2019), Saidani et al. (2019) and De Oliveira et al. (2021) differ, an own CE strategy coverage characterisation is used. In green, the two indicators that are more "complete" in terms of number of strategies encompassed according to the reviews are highlighted.

Table 15: CE strategies covered by the indicators analysed in this deliverable

Indicator (Source)	Strategies covered
Product-Level Circularity Metric (PLCM) (Linder et al., 2017)	reuse, remanufacture, and recycle
Material Circularity Indicator (MCI) (EMF & Granta, 2019)	reuse, recycling, landfill/energy recovery
Longevity (Franklin-Johnson et al., 2016)	reuse, refurbish and recycle
Circular Footprint Formula (CFF) (Zampori & Pant, 2019)	recycle, reuse, energy recovery, end-of-life
Product Circularity Indicator (PCI) (Bracquené et al., 2020)	recycle, reuse, energy recovery
Circularity indicator (Circ(T)) (Pauliuk et al., 2017)	recycle
Value-based Resource Efficiency (VRE) (Di Maio et al., 2017)	reuse, remanufacture and recycle
Sustainable Circular Index (SCI) (Azevedo et al., 2017)	recycle, reuse, repair and rethink (sharing), maintain, prolong
In-Use Occupation Ratio (UOR) and Final Retention in Society (FRS) (Moraga et al., 2021)	recycle, reuse and disposal (incineration without recovery)

Alejandrino et al. (2021) reviewed the way in which the different sustainability pillars have been implemented in 100 LCSA studies. As a side result, they found that less than 7% of the analysed studies address CE concepts or strategies. Among these, different circularity indicators for disposability, reusability or recyclability are used. However, widely-known indicators such as the Material Circularity Indicator (EMF & Granta, 2019) was not applied. To the best of our knowledge, there is no literature on the adaptation of the circularity indicators analysed in this deliverable to the operationalization of an integrated LCSA. Thus, the integration of CE strategies into an (operational) LCSA framework has not yet been accomplished. This means that ORIENTING will have to make a first attempt. The classifications from Moraga et al. (2019) and de Oliveira et al (2021) according to the life cycle thinking can help in this respect.

Rather than comparing different products, Cordella et al. (2021) compared scenarios with different combinations of CE measures from a carbon footprint and Life Cycle Costing perspective. Dedicated indicators for the CE measures were not used. As a result, if the aim was to assess the impacts in terms of sustainability of different CE measures, one could merely rely on scenario analyses, i.e., doing without dedicated CE indicators. The use of scenarios to addresses CE strategies will also be further considered in ORIENTING.

9.4 Defining the functional unit when extending a product’s or material’s lifetime

Different authors have addressed the issue of defining the functional unit when extending a product’s or material’s lifetime. A common practice is to set a reference time, common to conventional and extended use scenarios, and to consider the number of units of products needed in this period (see for example Iraldo et al. (2017)). Furthermore, material loops associated with reuse and recycling must also be considered. Niero and Olsen (2016) define the functional unit no longer from a pure product point of view (i.e., one can of beer disposed of after one use) but include a material point of view (i.e., 30 loops). The issue of limits to recycling (“finite loops”) underlying the latter study was also recently raised by Schaubroeck et al. (2021).

From a functional unit point of view, two different situations need to be distinguished:

1. If CE measures involve maintaining the same functions (repair, refurbish, …), then this prolongation of a product’s lifetime would not require to change the functional unit except for allowing and defining a longer lifetime.
2. If the 2nd (or later) life provides a different function (e.g. using ground coffee for briquets used in firing), then another approach must be followed. By default, system expansion is the option to choose in order to capture the different functionalities when sub-dividing a system into processes is not possible (ISO, 2006b).

In all other cases, allocating the burden and credits of recycling and using recycled materials is the main challenge. Even though not generally accepted, the Circular Footprint Formula (Zampori & Pant, 2019) is one potential candidate for addressing the allocation question of recycling.

9.5 Some reflections about life cycle stages

The product development/design stage is important for the overall environmental performance of a product during its life cycle. However, the environmental impacts occurring during the product development/design stage of many products will be rather limited. Nevertheless, this stage can be a substantial cost driver (economic pillar), involving also highly qualified personnel (social pillar, if evaluated).

From a social LCA perspective, two main stakeholder groups are distinguished by Goedkoop et al. (2018) that are mostly affected, i.e., stakeholders in the product value chain (workers, small-scale entrepreneurs and local communities) and users of products and services. While users are normally covered in LCA by the use stage, the other stakeholders are more distributed over a product’s life cycle. The examples that are provided in table 5.1 of Goedkoop et al. (2018) are: workers in recycling, waste handling, refurbishment, manufacturing and mining. These will be considered when reflecting about the life cycle stages to be distinguished in ORIENTING’s LCSA framework (see section 11.2.1).

As suggested by Goedkoop et al. (2018), product-service system thinking may also lead to a shift from workers in production to services. This would be identified when distinguishing between (use phase) maintenance and recycling on the one hand side, and mining and manufacturing on the other. The extent to which product-service system thinking will be adopted by the consumers appears to be an open question though (van Loon & Van Wassenhove, 2020).

Two CE-related Life Cycle Costing publications have been identified that, however, support the conclusions for social LCA, i.e., distinguishing the manufacturer from the consumer (Bradley et al., 2018) and including processes after the end-of life (Wouterszoon Jansen et al., 2020).[23]

10 Evaluation of different circularity approaches according to the ORIENTING criteria from T1.1

Table 16 provides an overview on the scoring of the different circularity approaches. In the following sub-sections, the evaluation of each individual circularity approach is presented. A more detailed description of the methods can be found in Annex C, section 13.3.

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[23] Bradley et al. (2018) further determine the percentage of reusable and of recoverable material at the manufacturer level and consider the costs of CE measures; at the consumer level, incentivised cost or reimbursement for returning the previous generation component (e.g. through buy-back programs). This has been dealt with in D1.3 on Life Cycle Costing.

Table 16: Overview on the scoring of the different material circularity approaches

#	(Sub-) Criterion	PLCM	MCI	Longevity	CFF	PCI	(Circ(T))	VRE	SCI	UOR/ FRS
III	Source	(Linder et al., 2017)	(EMF & Granta, 2019)	(Franklin-Johnson et al., 2016)	(Zampori & Pant, 2019)	(Bracquené et al., 2020)	(Pauliuk et al., 2017)	(Di Maio et al., 2017)	(Azevedo et al., 2017)	(Moraga et al., 2021)
XVII	**Overall Score**	**A-**	**A**	**A-**	**A-**	**A-**	**B**	**B**	**B+**	**A-**
1	**Stakeholder acceptance, credibility and suitability**	**C**	**A+**	**B**	**B**	**B+**	**C+**	**D+**	**B**	**B+**
1.1	Acceptance by Policy-makers	N/A	N/A	N/A	A	N/A	N/A	N/A	N/A	N/A
1.2	Accept. by Industry	C	A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
1.3	Accept. by Academia	D	A	C	C	A	B	C	C	C
1.4	Accept. by Civil society	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
1.5	Credibility among stakeholders	C	A	B	D	C	D	E	B	A
2	**Applicability / Complexity**	A+	B	A	A	B	C+	A	B	B+
2.1	Technical feasibility	A	A	A	A	A	A	A	A	A
2.2	Data availability and accessibility	A	N/A	B	B	C	C	A	C	C
2.2.a	for primary data (activity data)	N/A	C	N/A	N/A	N/A	N/A	N/A	N/A	N/A
2.2.b	for secondary data (activity data)	N/A	C	N/A	N/A	N/A	N/A	N/A	N/A	N/A
2.3	Data-intensity requirement	A	C	A	A	C	E	C	C	B
3	**Transparency**	A+	A	B	A	A	B+	C+	A	A+
3.1	Traceability of the modelling data and model used	A	A	C	A	A	D	A	*A*	A
3.2	Transparency of documentation	A	A	A	A	A	A	C	A	A
3.3	Reproducibility	N/A	C	C	C	C	A	E	C	A
4	**Scientific robustness**	A+	B	B	B+	B	B+	B	B+	A
4.1	Peer-reviewed or verification by 3rd party	A	A	A	A	A	A	A	A	A
4.2	State-of-the-art	A	A	A	A	A	A	A	A	A
4.3	Quality of the modelling data	N/A	C	C	B	N/A	C	N/A	C	N/A
4.4	Description of the uncertainties	N/A	E	E	E	E	C	E	D	C
5	**Completeness**	A+	A+	B+	B	A+	B+	A+	B+	C+
5.2	Ability to be applied to specific contexts	A	A	C	D	A	C	A	A	C
5.3	Ability to be generalized	A	A	A	A	A	A	A	C	A
6	**Compatibility with life-cycle approach**	C+	A+	A+	A+	A+	C+	B+	C+	A+
6.1	Life cycle thinking/approach	C	A	A	A	A	C	B	C	A

10.1 Product-Level Circularity Metric (PLCM)

Product-Level Circularity Metric (PLCM), C-metric (Circularity)

SCORE **A-**

DESCRIPTION

The Product-Level Circularity Metric (PLCM, C-metric) was published by Linder et al. (2017). Its quantitative method results in a single score indicator. While the methodology strongly relies on cost data, the metric is a simple ratio. So, there is a link to the economic dimension, but with low risk of double counting.

The authors propose a new circularity metric based on the use of product parts' economic value (expressed as costs, readily available to producers) as a basis for aggregating recirculated and non-recirculated elements into a combined measure of product-related circularity. This is calculated by iteratively adding the economic values and circularity of product parts over the whole value chain. The metric can enable customers and producers to contribute systematically to an increased degree of material recirculation. On purpose, the authors sought to develop/design a metric that only deals with circularity (i.e., without including e.g. environmental impacts or the issue of material criticality). An extensive list of examples can be found in Linder et al. (2020).

DEBATE

Nothing found.

CRITERIA

1. Stakeholder acceptance, credibility and suitability

The method is partially endorsed by industry. It can be understood and reproduced by researchers and analysts with moderate knowledge in the field. Further, it is a recently released method that seems to be promising. No information was found regarding the acceptance by policy-makers and by civil society organizations.

SCORE C

2. Applicability / Complexity

The calculation can be done with standard freely available software tools. General data is available for free in appropriate formats without restrictions. Very low (foreground) data requirements to generate results with the method, when compared to other circularity methods.

SCORE A+

3. Transparency

The methodological specifications are continuously available. All methodological choices are clearly documented. Documentation allows reproducibility[24], however, noting that company internal data is needed.

SCORE A+

4. Scientific robustness

The method has been peer reviewed in the scientific literature and reflects up-to-date knowledge on the topic (published in 2017). The method only uses (cost) data available to companies. The quality of the modelling data and parameter uncertainty could not be

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[24] Note that sub-criterion 3.3 on "Reproducibility" only evaluated the available documentation, not the availability of data.

evaluated because the method does not use parameters (but only primary data from the companies).[25]

SCORE A+

5. Completeness
The method can be applied to specific contexts. It can be generalised without the need to adapt the methodological steps (e.g. assumptions, parameters, etc).

SCORE A+

6. Compatibility with life-cycle approach
CE strategies are assessed taking a partial LCT approach in terms of LC stages.

SCORE C+

COMMENTS
none

10.2 Material Circularity Indicator (MCI)

Material Circularity Indicator (MCI)
(Circularity)

SCORE **A**

DESCRIPTION
The Material Circularity Indicator (MCI) is an indicator for products and was developed by the Ellen MacArthur Foundation (EMF & Granta, 2019). The 2019 update also considers biological cycles. The quantitative method results in a single score indicator that is not related to any other sustainability dimension. The MCI measures the extent to which linear flows have been minimized and restorative flows maximized for the component materials of a product, and for how long and intensively the materials are used compared to a similar industry-average product. The result is a value between 0 and 1 where relatively higher values indicate a higher circularity. The calculation itself considers: the mass flows in the life cycle; the utility or function of the product via timespan of usage (including

CRITERIA

1. Stakeholder acceptance, credibility and suitability
The method is endorsed by most sectors of industrial economy. It is also well trusted by international research bodies. The method can easily be understood and reproduced by non-experts in the field. No information was found regarding the acceptance by policy-makers and by civil society organizations.

SCORE A+

2. Applicability / Complexity
The calculation can be done with standard freely available software tools. General data is available, but needs adaptations. In addition, specific data from industry or companies is required. Medium (foreground) data requirements to generate results provided by the method, when compared to other circularity methods.

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[25] Note that sub-criterion 4.4. related to uncertainty posed the question “*To what extent is there an explicit statement of the uncertainty associated with the parameters behind the modelling data, that may affect the final results of the assessment, e.g., in terms of standard deviation, range of values, order of magnitude (Result uncertainty)?*”. This was only related to parameter uncertainty, noting that the method does not use parameters. Likewise, sub-criterion 4.3 on quality only refers to “modelling data”.

durability of products, repair/ maintenance and shared consumption business models) and intensity of usage; rates and flows at the EoL that are going to landfill (or energy recovery), collected for recycling and collected for reuse; the rates and flows of recyclable materials; composting and energy recovery from biological materials. Data is mostly retrieved from companies. In addition, average data on the product analysed is needed as well. The MCI is intended for product analysis, but could also be used to build up a circularity profile for a company. The indicator targets the decision-makers at industries. The method concerns the product- or company-level and is widely known. It does not directly support policy-makers.

The methodology relies on similar values (mass and rates) as used by practitioners conducting LCA or criticality assessment. For these interest groups, the method is transparent and easily understandable.

DEBATE

The VITO report – Summa project (Van Hoof et al., 2018) comments as follows: "Given the scope (micro), it is evident that improving the MCI of a product or a company will not necessarily translate as an improvement of the circularity of the whole system. Nonetheless, a widespread use of this methodology could form part of such a systems improvement. Further a lot of pros and cons were mentioned and discussed. Proposing to improve the MCI, Bracquené et al. (2020) criticize 5 relevant points.[26]

The 2019 update also considers biological cycles that had previously been missing according to Razza et al. (2020).

SCORE B

3. Transparency

The methodological specifications are continuously available. All methodological choices are clearly documented. The results are reproducible if primary data is available.

SCORE A

4. Scientific robustness

The method has been peer reviewed and reflects up-to-date knowledge. The modelling data fits minimum requirements regarding representativeness and/or quality. No documentation was found regarding the methodology uncertainties.

SCORE B

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[26] The five points are Bracquené et al. (2020): 1) not accounting fort he tightness of the material cycles, 2) ignoring „where the reused components and recycled materials are sourced from and where the recovered components and materials will end up“, 3) disregarding the effect of downcycling, 4) ignoring manufacturing stages other than recycled feedstock production (notably as virgin feedstock production) and 5) the fraction of recycled material content and fraction of reused components are both defined at product or component level (i.e., not completely independent in the MCI model).

COMMENTS
none

5. Completeness
The methodology can be applied to a specific context. Further, the method can be generalised without the need to adapt the methodological steps (e.g. assumptions, parameters).

SCORE A+

6. Compatibility with life-cycle approach
CE strategies are assessed taking a full LCT approach in terms of LC stages.

SCORE A+

10.3 Longevity

Longevity
(Circularity)

SCORE A-

DESCRIPTION
The longevity indicator measures the contribution to material retention based on the amount of time a resource is kept in use in a product system (Franklin-Johnson et al., 2016). Calculations are temporally resolved (in months). It includes also an initial lifetime (the total time of new material in use), earned refurbished lifetime (based on the refurbished or reused material - one or two times) and earned recycled lifetime (time that recycling adds to the lifetime of a material when used in a new products). Longevity is the sum of these three variables. The indicator is dedicated to evaluate products, including their components and materials. The intended audience is the industries. The quantitative method results in three single indicators that are used to inform design issues. They could also be aggregated into one indicator (single score). The method does not overlap with other sustainability fields.

DEBATE
From the discussion of limitations in Franklin-Johnson et al. (2016) :
The indicator is a simple way to measure circularity, but might overly simplify the supply chain. It focuses the analysis ”on materials and

CRITERIA

1. Stakeholder acceptance, credibility and suitability
No information was found related to the acceptance either by policy-makers or by the industry and civil society. The method is promoted by individual researchers and cited by Moraga et al. (2019) and Saidani et al. (2019). The methodology can easily be understood and reproduced by those with basic knowledge in the field.

SCORE B

2. Applicability / Complexity
Calculations can be done with standard freely available software. General data is available with some restrictions. The authors refer to the primary data sources as “exchanges with industry experts” and to secondary data sources as “literature and industry reports”. Few data is needed. However, data on recycling, refurbishing and reuse rates for specific products, components or materials might not be available.

SCORE A

3. Transparency
Few methodological specifications are continuously available. Primary data might be confidential, results might therefore not be reproducible for every case even if the methodology is.

SCORE B

objects in pre-existing product systems and for items which have already been purchased by customers". The life-cycle perspective does not consider particularities of refurbishment and recycling processes and assume that the products (or parts thereof) are reused in similar products which is a methodological choice rather than reality. In this sense, "down-cycling (the creation of lower quality products with recycled materials) is not addressed". The calculation also does not consider additional (primary or secondary) materials needed for the refurbishment, neither the consumption of any other resources in the life-cycle.

COMMENTS
none

4. Scientific robustness
The method has been peer reviewed or verified by a third party. It reflects the up-to-date knowledge on the topic, despite the publication being somewhat dated (2016). The modelling data fits minimum requirements regarding representativeness and quality. There is no documentation of the uncertainties (at least no information was found).

SCORE B

5. Completeness
The method seems to work for both company-specific product analysis and average product analysis. No restrictions to the method are mentioned.

SCORE B+

6. Compatibility with life-cycle approach
CE strategies are assessed taking a full LCT approach in terms of LC stages.

SCORE A+

10.4 Circular Footprint Formula (CFF)

Circular Footprint Formula (CFF)
(Circularity)

SCORE **A-**

DESCRIPTION
The method Circular Footprint Formula (CFF) from Zampori and Pant (2019) is recommended by the European Union for calculating the product environmental footprint (PEF). The method is quantitative and comprises three equations. By assessing the end-of-life of a product in an LCA, the formulae are used to allocate burdens and

CRITERIA

1. Stakeholder acceptance, credibility and suitability
The method is endorsed by the EU and is promoted further by research groups. The method can only be understood and reproduced by LCA specialists. No information was found regarding the acceptance by industry and civil society organizations.

SCORE B

credits between suppliers and users of recycled (or reused) materials and recovered energy and to determine the environmental burden (releases and use of resources) of final disposal. It is generically applicable to final products and intermediate products.

DEBATE

The CFF is criticised for not maintaining the mass balance due to the quality correction and further for containing many parameters, making it more complex to use in practice while acknowledging that it is more comprehensive compared to the other approaches (Malabi Eberhardt et al., 2020). Another group of authors criticises the CFF because it does not account for the number of times a material is recycled (except for packaging). Further a quality factor of 1 for metals and many plastic materials is questionable and the quality in some cases depends on the previous use (e.g. printing paper vs. glossy paper). At least the crediting is limited to values between 20% and 80% while ISO allows up to 100% (Bach et al., 2018). Bach et al. (2018) “recommend to review and revise the quality terms and allocation factors and to consider reuse rates for all materials and products”. They suggest: “One simple solution to improve the CFF would be to adapt the specifications of ISO for closed loop recycling.”

COMMENTS

Different from the other methods included in this evaluation, the result is not intended to be used stand-alone although metrics can be derived from it.

The quality terms constitute subjective elements.

The formulae themselves contain releases and resource uses and thus overlap with environmental LCA.

2. Applicability / Complexity

The calculations can be done with standard freely available software tools. However, the result would need to be integrated into an LCA tool and the inclusion of emissions/releases and resource uses would best be done in LCA tools. General data is available and further default data is provided. The methodology could therefore be updated accordingly. Very low data requirements to generate results.

SCORE A

3. Transparency

The methodological specifications are continuously available. All methodological choices are clearly documented. The results might be reproduced based on existing data. The formulae contain LCI data (releases and resource use), which leads to a dependency of the results on the data basis used.

SCORE A

4. Scientific robustness

The method has been verified by third party and was proposed at the end of the PEF pilot phase in the course of which the original EoL formula had been road-tested/criticised and subsequently modified. The method reflects the up-to-date knowledge on the topic. The available data has acceptable representativeness and quality. Documentation regarding uncertainties of the methodology was not found.

SCORE B+

5. Completeness

The method can be applied to specific contexts with some effort. Data could be used that are generic to the EU or a given sector therein. The elementary flows to be considered shall be “specific”. The other parameters are at least specific to the EU, if not country specific, but not specific to a site. So, some data can be specific to a site but not all.

The method can be generalised without the need to adapt the methodological steps (e.g. assumptions, parameters).

SCORE B

6. Compatibility with life-cycle approach

The CFF was developed for the purpose of an environmental LCA as part of the PEF. So, the CE strategies are assessed taking a full LCT approach in terms of LC stages.

SCORE A+

10.5 Product Circularity Indicator (PCI)

Product Circularity Indicator (PCI)

(Circularity)

SCORE **A-**

DESCRIPTION

Developed by Bracquené et al. (2020), the Product Circularity Indicator (PCI) is a further development on the Material Circularity Index (MCI) from Ellen MacArthur Foundation. The quantitative method results in one indicator and there are no overlaps regarding other sustainability fields.

The PCI gives a value between 0 and 1 where relatively higher values indicate a higher circularity. The PCI is a product-level circularity indicator. In Bracquené et al. (2020), it has been applied to washing machines as an illustration. The intended audience is not explicitly mentioned, but probably similar to the audience of the MCI indicator, i.e., decision-makers in industries.

DEBATE

Very recently developed indicator, so no critique found yet. Bracquené et al. (2020) themselves state that the PCI overcomes some of the limitations of the MCI indicator, while there still are remaining limitations (such as the fact that the different quality of recycled materials is not taken into account, and the mining or material extraction stage is not included).

CRITERIA

1. Stakeholder acceptance, credibility and suitability

The method is well trusted by international research groups, because the methodology background is the well-known MCI indicator. There is no information on the acceptancy by policy makers, by industry as well as by civil society. The method can be understood and reproduced by researchers and analyst with moderate knowledge in the field.

SCORE B+

2. Applicability / Complexity

The method can be calculated with standard freely available software tools. General data is available. Both company specific primary data and secondary data at a larger scale (region, country, global) are required. The data requirements to generate results provided by the method is difficult to judge, but estimated as medium.

SCORE B

3. Transparency

It is a recent method for which full methodological specifications are continuously available. The methodological choices are clearly documented. The results are reproducible if existing data is available.

SCORE A

4. Scientific robustness

The method has been peer reviewed in the scientific literature. It reflects up-to-date knowledge on the topic. There is no specific modelling data needed. All data need to be provided by the practitioner conducting the assessment. There is no information available regarding the uncertainties of the method.

SCORE B

COMMENTS
none

5. Completeness
The method can be applied to specific contexts. It can be generalised without the need to adapt the methodological steps (e.g. assumptions, parameters).

SCORE A+

6. Compatibility with life-cycle approach
CE strategies are assessed taking a full LCT approach in terms of LC stages.

SCORE A+

10.6 Circularity index (Circ(T))

Circularity index (Circ(T))
(Circularity)

SCORE **B**

DESCRIPTION
Developed by Pauliuk et al. (2017), the circularity index Circ(T) method is quantitative and results in one indicator. The indicator itself does not overlap with other sustainability dimensions. Circ(T) is a performance indicator for the circularity of a material. It is defined as a relative measure of the cumulative mass of a material (e.g. steel) present in the system over a certain time interval in terms of an ideal reference case, where all material remains in functional applications throughout the entire accounting period. Circ(T) denotes the cumulative service provided by a material/product over a certain time span as a fraction of the maximal service possible (i.e., it is bounded by 0 and 1). Material loss and degradation are the two reasons why Circ(T) is smaller than 1 in all realistic cases. Similar to the global warming potential, Circ(T) varies depending on the chosen (reference) time horizon T. Circ(T) is a performance indicator for the circularity exemplified in a case study on by steel use throughout several life cycles (goal: maintain utility), that can be calculated from the based on scenario results of MaTrace Global, a multiregional extension of MaTrace (Nakamura et al., 2014) with global scope (Pauliuk et al., 2017). MaTrace Global is a supply-driven multiregional model of steel flows coupled to a dynamic stock model of steel use. According to different scenarios, annual results show how steel consumed in

CRITERIA

1. Stakeholder acceptance, credibility and suitability
The method is well trusted by European research bodies. It was cited 44 times since its publication. No information was found regarding the acceptance by policy-makers, industry and in civil society organisations. The method can be only understood and reproduced by specialists. The indicator relies on the MaTrace Global model, which can only be used by specialists.

SCORE C+

2. Applicability / Complexity
The calculation can be done with standard freely available software tools. The complete MaTrace Global model (Python script with the model calculations and Excel file with the data and scenario parameters) is available as supplementary material. Python is a freely available software. The method requires specific data from an industry and company. The available MaTrace Global model currently is limited to steel. Further, very high (foreground) data requirements exist.

different countries are distributed across regions and products up to the year 2100.This can be used to analyse how current and anticipated technological options change the product distribution of steel in the future and reduce losses and thus improve circularity. MaTrace allows for tracing a certain unit of a recycled material through the supply chain. The model combines a dynamic stock model of the use phase of a material with a linear model of the waste management industries, the remelting processes, the manufacturing sectors, and the markets for End of Life products, i.e., scrap, secondary metals, and final products. The method is focused on single materials over multiple product cycles; only applied to steel so far.

DEBATE

Pauliuk et al. (2017) state themselves that "it complements demand-driven assessments based on the Leontief-IO approach, including LCA, that estimate the total industrial activity required to produce a unit of consumption. While LCA allows modelers to study different material inputs for a single product, MaTrace studies how a single material is distributed across different products. MaTrace thus helps modelers to depict the complexity of the recycling network. MaTrace faces similar limitations as LCA regarding the indeterminacy of future technological and trade pattern developments and regarding scalability. […] The assumption of constant technology and trade patterns is a major limitation that MaTrace shares with other bottom-up approaches, especially attributional LCA."

COMMENTS

none

SCORE C+

3. Transparency

Methodological specifications are available but incomplete. The methodological choices are clearly documented. The results can easily be reproduced. Further, the model equations, the assumptions for the parameters, and the data sources used are presented in detail. The complete model (Python script with the model calculations and Excel file with the data and scenario parameters) is available, too.

SCORE B+

4. Scientific robustness

The method has been peer reviewed in the scientific literature. It reflects the up-to-date knowledge on the topic. Modelling data fits minimum requirements regarding representativeness and quality. Available data is adequate for steel but lacking for all other materials. Uncertainty estimates are provided, motivated and reported in qualitative terms.

SCORE B+

5. Completeness

The method can be applied to specific contexts if context-specific information is made available (have to be collected). Further, it can be generalised without the need to adapt the methodological steps (e.g. assumptions, parameters, etc). The regional scope of the MaTrace model (Nakamura et al., 2014) has been extended in MaTrace Global to cover the whole world economy subdivided into 25 regions.

SCORE B+

6. Compatibility with life-cycle approach
CE strategies are assessed taking a partial LCT approach in terms of LC stages, because the mining or material extraction stage is not included.

SCORE C+

10.7 Value-based resource efficiency (VRE)

Value-based resource efficiency (VRE) (Circularity) SCORE **B**

DESCRIPTION
The value-based resource efficiency (VRE) method was developed by Di Maio et al. (2017). The quantitative method results in a single score indicator and includes elements of other sustainability fields (criticality). Further, the method is a new value-based indicator assessing the performance of actors in the supply chain in terms of resource efficiency and circular economy. The method measures both resource efficiency and circular economy in terms of the market value of so-called "stressed" [= scarce] resources since this value incorporates the elements of scarcity versus competition as well as taxes representing urgent social and environmental externalities. Di Maio et al. (2017) define circularity as "the percentage of the value of stressed resources incorporated in a service or product that is returned after its end-of-life" whereas "Resource efficiency is the ratio of added product value divided by the value of stressed resources used in production or a process thereof".

DEBATE
Nothing found.

CRITERIA

1. Stakeholder acceptance, credibility and suitability
The article has been cited 64 times, so it is well known by some research groups. Regarding the acceptancy by policy-makers, industries and civil society organizations, no information was available. The method itself is not transparent, nor easily to understood.

SCORE D+

2. Applicability / Complexity
The VRE can be calculated with standard available software tools. General data is available. Regarding the data intensity, it has not become clear how much data is actually needed. But even if a lot of data is needed, it appears to be available from the indicated sources.

SCORE A

3. Transparency
The methodological specifications are continuously available. Not all methodological choices are stated, e.g. it is not clear what is meant by "stressed" resources. In addition, the documentation to reproduce the results is not detailed enough.

SCORE C+

COMMENTS

The paper appears to be more on resource efficiency in view of scarce/critical materials rather than on circularity as such. The article cites only a few, partly outdated publications. It also makes many statements without sufficient support (i.e., demonstrated by own analyses or other studies). Similarly, Di Maio et al. (2017) claim to introduce also a dedicated circularity metric (different from the resource efficiency metric) but never come to suggest a related computation. They distinguish the VRE for processes and for products, but appear to get mixed up in the computation of the one or the other (3rd last paragraph of chapter 5).

4. Scientific robustness

The method has been published in a peer-reviewed scientific journal with a high impact factor. It reflects up-to-date knowledge due to the recent publication date. No information was found neither regarding the quality of the modelling data[27] nor regarding the uncertainties of the method.

SCORE B

5. Completeness

The methodology can be applied to specific contexts. It is possible to use site-specific data or value-chain specific data. The method itself can be generalised without the need to adapt the methodological steps (e.g. assumptions, parameters, etc). The conducted case study is very macro (=national level).

SCORE A+

6. Compatibility with life-cycle approach

Environmental or social considerations are not dealt with, but value chain analyses are possible in economic terms.

SCORE B+

10.8 Sustainable Circular Index (SCI)

Sustainable Circular Index (SCI)

(Circularity)

SCORE **B+**

DESCRIPTION

The method by Azevedo et al. (2017) is based on a five-phase framework to calculate a Sustainable Circular Index (SCI) as a benchmarking tool for manufacturing companies. The five stages are indicator selection, (Delphi based) weighting, normalisation, aggregation and index construction. Suggested indicators for

CRITERIA

1. Stakeholder acceptance, credibility and suitability

The method is accepted by academia and was cited 39 times. No information was found regarding the acceptance by policy-makers, by industries and by civil society organizations. The method can easily be understood and reproduced by those with basic knowledge in the field.

SCORE B

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[27] Note that sub-criterion 4.3 on quality only refers to “modelling data” while this method does not need parameters.

circularity are "Input in production process" (virgin/recycled/reused), "Utility during use phase" (lifetime and lifecycles) and "Efficiency of recycling". They are complemented with indicators for environmental, social and economic aspects. The intended application is to support decision making in manufacturing companies towards circularity and sustainability. The quantitative method results in a single score result. As mentioned before, the method includes elements of other sustainability dimensions. As it includes sustainability indicators, it overlaps with all three sustainability domains.

DEBATE

Nothing found.

COMMENTS

As the full-scale assessment is unfeasible for ORIENTING, only the product-related circularity part is evaluated

2. Applicability / Complexity

The calculations of the SCI can be done with standard and freely available software tools. The calculation is straightforward if data is available. Some of the data must be gathered by the companies itself, some are based on publicly available sources and some are based on expert judgements, especially regarding lifecycles and lifetime.

SCORE B

3. Transparency

Methodological specifications are continuously available. The method documentation is from the year 2017. The methodological choices are clearly documented. It constitutes just a calculation framework (i.e., no indicators provided).

SCORE A

4. Scientific robustness

The method has been peer-reviewed in the scientific literature. The article was cited 39 times since its publication in 2017. It reflects up-to-date knowledge, but no modelling data is provided. Information regarding uncertainties is not available.

SCORE B+

5. Completeness

The method itself can be applied to specific contexts. It can be generalised, which however would require extensive changes.

SCORE B+

6. Compatibility with life-cycle approach

CE strategies are assessed taking a partial LCT approach in terms of LC stages. There are no life cycle thinking (LCT) considerations, but indicators make use of LCT elements.

SCORE C+

10.9 In-use occupation based indicators

In-use occupation-based indicators
(Circularity)

SCORE **A-**

DESCRIPTION

In-use occupation based indicators was developed by Moraga et al. (2021). It is a quantitative method which results in two indicators. There is no overlapping to other sustainability fields.

The method comprises two indicators: in-use occupation ratio (UOR) and final retention in society (FRS). UOR is the percentage ratio between the in-use occupation along the product cycles and the theoretical maximum in-use occupation, that is, the performance of the entire occupation for the use of the material within the time horizon. The FRS shows the remaining percentage of the primary raw material at year 25. Two application cases are shown: 1) laptop and 2) wood floor product.

DEBATE

Discussion by Moraga et al. (2021):

- Positive: take time into account, not attached to a single product cycle, suitable for policymaking, results based on in-use occupation can be presented in comprehensible graphical plots.
- Negative: do not take into consideration the quality of the material, wood cannot be reversed to its raw material state at EoL, which makes the differences in quality even more evident, explanation: quality is a controversial subject and “is the foremost critical factor” in the waste management system.

COMMENTS

none

CRITERIA

1. Stakeholder acceptance, credibility and suitability

Due to the recent publication date, no information regarding acceptance was available. The method is promoted by an individual group of researchers. The method can easily be understood and reproduced by non-experts in the field.

SCORE B+

2. Applicability / Complexity

The calculation of the methodology can be done by freely available software tools. General data is available but the method requires specific data from industry or companies.

SCORE B+

3. Transparency

Full methodological specifications are continuously available. The methodological choices are clearly documented and the results can easily be reproduced.

SCORE A+

4. Scientific robustness

The method is published in peer reviewed scientific literature. It reflects the up-to date knowledge on the topic. Uncertainty estimates are provided, motivated and reported in qualitative terms, especially regarding time horizon.

SCORE A

5. Completeness

The method can be applied to specific contexts if context-specific information is made available (have to be collected). It can be generalised without the need to adapt the methodological steps (e.g. assumptions, parameters).

SCORE C+

6. Compatibility with life-cycle approach

Circular economy strategies are assessed taking a full life cycle thinking approach in terms of life cycle stages.

SCORE A+

11 Conclusions

The conclusions start with a consideration on what European policy seeks to achieve with CE strategies. Notably according to the EC's Circular Economy Action Plan 2.0 (CEAP2.0) (European Commission, 2020a), CE is a concept to reduce "biodiversity loss and water stress", achieving "climate neutrality by 2050 and decoupling economic growth from resource use" such as to "keeping its resource consumption within planetary boundaries". As a result, circular economy strategies – at least from a European Union's perspective – are a means to achieve the ends of lowering biodiversity loss, reducing water stress and resource uses in general, and achieving carbon neutrality. It can be noted that for each single "end", just listed, there are corresponding impact categories usually evaluated in any LCA, including the Product Environmental Footprint (Zampori & Pant, 2019). LCA is also identified to be the approach of choice to evaluate the environmental sustainability of measures seeking to reduce consumption of materials and production of waste, i.e., the goal of CE, while also noting shortcomings (Peña et al., 2021; van Loon et al., 2021).

In the CEAP 2.0, material criticality, dealt with in Part 1 of this deliverable, is only once alluded to in terms of "security of supply" for batteries. Nevertheless, this link is established from a critical raw material point of view in the regular reports by the European Commission on critical raw materials (e.g. European Commission, 2020c). In order to reduce supply risks, the European Union should be interested in keeping critical (raw) materials in their boundaries (through CE strategies). This has also been emphasised by a recent OECD publication (IEA, 2021). Therefore, this is one of the links of criticality (Part 1) and circular economy (Part 2) in the framework of ORIENTING.

In view of the many publications available on CE dealing with a multitude of products (see section 11.2), a rigorous pre-selection was conducted (see chapter 8), resulting in nine methods that have been evaluated against the T1.1 criteria:

1. Longevity indicator (Franklin-Johnson et al., 2016),
2. Product-Level Circularity Metric (PLCM, C-metric) (Linder et al., 2017, 2020),
3. Material Circularity Indicator (MCI) (EMF & Granta, 2019),
4. Circularity index Circ(T) (Pauliuk et al., 2017),
5. Value-based resource efficiency (VRE) method (Di Maio et al., 2017),
6. Sustainable Circular Index (SCI) (Azevedo et al., 2017),
7. Circular Footprint Formula (CFF) (Zampori & Pant, 2019),
8. Product Circularity Indicator (PCI) (Bracquené et al., 2020),
9. In-use occupation ratio (UOR) and final retention in society (FRS) (Moraga et al., 2021)

An important aspect is that most of these CE indicators are relative-based indicators (e.g. providing output indicators in percentages). However, in order to use their results in a LCSA framework, providing proper guidance on how to set targets, for instance, certain adjustments into absolute terms (e.g. in quantity of mass) are needed.

Before giving recommendations as to which of these methods should be further analysed in WP2, general conclusions on CE strategies, their measurement and business uptake are presented.

11.1 General conclusions on CE strategies, their measurement and business uptake

The following conclusions are drawn from research completed in 2017-18 with a sample of 39 companies and a review of 140 company reports (WBCSD, 2018). The responses mentioned below primarily relate to the interviews that were completed with the companies.

The report uses the terms “indicators” and “metrics” inter-changeably. Also, the notion “key performance indicator” (KPI) is introduced. This indicated that the distinctions between the two terms had not been entirely recognised, this might as a function of the author’s limited experience in the area and/or due to the early stage of the development of CE performance measurement thinking.

1. The interviews indicated that circularity in companies is being driven by business performance and therefore measurement, metrics, indicators, KPIs, etc, will be of growing importance for internal performance measurement (business, process and products levels), but also for external communications to customers, suppliers, reporting and rating agencies. However, the majority of circularity measurement was being explored is at company level rather than a product level.
2. Materials fall within scope in 100% of interviews; however, energy, water, etc, is defined as being part of circularity measurement in a high number of instances. This indicates that there was a potentially very broad definition of circularity being used at that stage for many companies interviewed and the need for more robust universally agreed definition is needed, which further reinforces the importance of the activities within ISO TC323 WG1. Furthermore, also a number of the metrics presented in the report could be argued to be outside the scope of circularity measurement (WBCSD, 2018).
3. Based on a review over 140 company reports completed in the study (WBCSD, 2018), the life cycle stages most frequently addressed by existing metrics appear to be Raw Materials and End of Life, perhaps driven by previous internal work on eco-efficiency and resource efficiency, as well as external drivers from stakeholders. It can also be noted that at the time of research, most CE metrics are focused on a process and operational level.
4. Reference to life cycle and life cycle stages is made in most CE initiatives and circularity assessment methods
5. Four tools appear particularly useful to support the assessment of “product circularity” and “materials circularity”:
    - LCA is mentioned at a general level to assess impacts of product circularity
    - The other tools mentioned should be analysed e.g. MCI (EMF, see chapter 10), CET (EMF), CEIP (WBCSD)
    - Connection should be explored with EMF and WBCSD in the future as their CE metrics work will have evolved since May 2018

The study indicated that in 2018, companies were at different levels of maturity of circularity performance measurement. Significant advances have been made since then (see section 13.1.6). In terms of CE performance measurement, it is perhaps the advanced companies that will be drilling down into products, lifecycle thinking and LCA. In addition, also advanced companies that have historically used LCA may be looking developing in-house CE metrics vis a vis LCA such as ABB and BASF.

At a national level, the European Commission (EC) put forward resource efficiency indicators within the Roadmap to Resource Efficiency Europe in 2011.As a result Eurostat developed a database to support resource efficiency indicators development. Based on that data, EU Resource Efficiency Scoreboard was published in 2014 and 2015. After 2015 and perhaps the CEAP 1.0, there appears to be a broadening of thinking from the EC from thinking about resource efficiency indicators to CE indicators. To foster this shift, the EC has launched substantial new activities on CE monitoring at a European and national level working through the Bellagio Declaration that is being led by European Environment Agency (EEA) and others (ISPRA & EEA, 2020). Japan has a long tradition at a national level, company and product level over indicators and metrics related to resource efficiency, resource productivity and eco-efficiency linked to the diffusion of the concept of a movement towards a Sound Material-Cycle Society.

11.2 Recommendations on how to consider CE strategies in an LCSA framework

11.2.1 Consideration at different levels: Functional unit/reference flow, life cycle stages and dedicated indicators as well as scenarios

Based on the considerations about functional units (see section 9.4), life cycle stages (7.2) and indicators (10), the ORIENTING LCSA framework could address the different CE strategies in the following way:

- Adapting the **functional unit and proper definition of the reference flow:** some CE strategies aim at an extension of the lifetime of a product (e.g. through repair and refurbishment), while maintaining other functional characteristics similar to conventionally linear products. This implies assessing impacts associated with the production, use and disposal of products during a reference time. By contrast, for the reuse of materials or parts in products of the same or (entirely) different functionality (e.g. through up- or down-cycling), a different approach (than through properly defining the functional unit and the reference flow) is needed (e.g. dedicated indicators).
- Distinguishing **life cycle stages** according to relevant steps in a CE: mining/resource extraction stage, product development/design stage (i.e., separate from manufacturing), manufacturing (and re-manufacturing, where necessary), transportation/distribution processes, use phase (relevant to understand the "weight" of CE strategies), maintenance, repair and refurbishment of the product (i.e., separate from product use), and, finally, the End-of-Life (e.g. recycling, energy recovery, landfill, unused stock). From a social LCA perspective, the stakeholders mentioned in table 5.1 of Goedkoop et al. (2018) correspond largely to the stages listed above when also making the End of Life stage more granular and adding a "waste handling/collection" stage (see section 9.5). The environmental impacts during the product development/design stage of many products will be rather limited. Nevertheless, this stage can have a dramatic influence on the entire life cycle impacts, apart from being a substantial cost driver (economic pillar) in which qualified personnel is involved (social pillar, if evaluated).
- Introducing **dedicated CE indicators** (in addition to the environmental, social and economic indicators): if the aim was to assess the impacts in terms of sustainability of different CE measures, one could merely rely on scenario analyses, i.e., doing without dedicated CE indicators (e.g. Cordella et al., 2021). If a product should be characterised regarding its circularity in a quantitative way, however, dedicated CE indicators at product level are needed. In view of the different materials to be addressed and measures to be taken at different stages of a product's life cycle, considering several CE indicators is recommended by several authors (Helander et al., 2019; Pauliuk, 2018). Obviously, different types of CE indicators exist (e.g. weight or volume of a product, percentage (relative to total weight) or amount of recycled or virgin material, percentage (relative to total weight) or amount of recycled or virgin critical raw material, percentage of renewable material, number of re-used components, amount of hazardous substances contained in a product). See section 11.2.2, for a more specific reflection.

While the adaptation of the functional unit to explicitly specify the lifetime of a product and distinguishing further life cycle stages of relevance for CE measures is straightforward, establishing a balanced list of dedicated CE indicators is more challenging. According to ORIENTING's Description of Work, the "ultimate goal" regarding circularity metrics to be considered in the LCSA framework is "*to unveil and inform on potential trade-offs of circularity systems versus environmental priorities in a consistent and visually expressive way*". It is supposed that "circularity systems" is understood as "CE strategies" and "environmental priorities" alludes to sustainability in general; note that visualisation is dealt with in WP2 and WP3. To this end, ORIENTING seeks to "*propose an operational approach to incorporate circularity aspects in the LCSA*" through "*defining and* *incorporating a set of operational indicators, aligned with the LCSA methodology, which can provide information on critical circularity features of products*".

Finally, several CE measures or strategies are available that a product can be subjected to in its life cycle. Because different combinations of CE measures or strategies might be pursued in a product's life cycle, WP2 could explore ways to define scenarios with different CE measures or strategies for a given product that are consistent and allow a fair comparison. This might involve adjusting the functional unit and system boundaries as well.

11.2.2 Dedicated CE indicators

When trying to identify the CE indicators to be integrated into ORIENTING'S LCSA framework, several aspects need to be considered. Consistently unveiling and informing about trade-offs between CE measures and implications in terms of sustainability can be done in different ways. Broadly, two ways can be distinguished: 1) If only the trade-off between efforts towards CE generally undertaken in a product's life cycle and sustainability implications should be identifiable, rather general indicators of CE measures would suffice. 2) If, however, the implications of individual CE measures should be traceable, then this would require to have CE indicators that measure CE actions in a rather detailed way. In either case, the indicators need to be operational and aligned with the LCSA methodology. The latter appears to say that the CE indicators need to fit into the life cycle framework of which the defined functional unit and the distinguished life cycle stages have already been mentioned as important elements (see section 11.2.1). As regards degree of granularity, a pragmatic solution needs to be found with a manageable number of indicators that could range from the 3Rs distinguished in section 7.2 according to Cordella et al. (2020) to more elaborate schemes such as the 9Rs suggested by Potting et al. (2017) or UNEP (2019b). Identifying indicators per CE strategy at a high granularity was not a guiding principle in the literature search and prioritisation of this Task.

The evaluation against the T1.1 criteria in chapter 10 resulted in relatively high overall ratings (between A and B) for all analysed circularity methods. The highest overall score (A) has resulted for MCI, closely followed by PCI, PLCM, Longevity, the CFF and UOR/FRS (all A-). The lowest score (B) was obtained for the methods Circ(T) and VRE (SCI scoring B+). This overall ranking has resulted from assigning equal weight to all sub-criteria and averaging over the sum of their scores. The question, however, is whether all sub-criteria should be assigned equal importance.

In view of what the ORIENTING project has promised regarding product-related circularity, key features are operationality (addressed by the criteria 2 "applicability", including data availability and accessibility aspects, and 6 "Compatibility with life-cycle approach"), providing critical circularity information of products (partly addressed by sub-criterion 5.2 "Ability to be applied to specific contexts"), and alignment with the LCSA methodology (partly also addressed by criterion 6 "Compatibility with life-cycle approach").

For operationality in terms of applicability, PLCM scores highest (A+), closely followed by Longevity, the CFF and VRE (all A). MCI, PCI, Longevity, CFF and UOR/FRS methods instead score highest (A) for compatibility with the life cycle approach (including aspects of operationality). Regarding the CFF, it is worth mentioning that it is endorsed by the European Commission in the context of the environmental LCA "Product Environmental Footprint", already identified to be relied upon within ORIENTING. It needs to be noted, however, that the CFF is conceived to mainly serve as an allocation procedure and thus does not constitute a stand-alone indicator (see below). All methods apart the SCI equally score A for context-specific assessments. None of these methods has issues in terms of double counting (e.g. also including environmental impacts), noting that some methods rely on data from the other domains (e.g. costs used by the PLCM). In terms of granularity, all of the analysed methods capture reuse and recycling while only Circ(T) and VRE cover any strategy (Table 17). As a final note, PLCM (A+) and UOR/FRS (A) are the methods with the highest scientific robustness, the others ranking between B and B+.

Table 17: Degree to which the analysed methods cover CE strategies

Name of the CE indicator (source)	Reuse	Repair	Refurbish/ remanufacture	Recycle	Energy recovery	Landfill	Comment
Longevity (Franklin-Johnson et al., 2016)	x		x (ref.)	x			
PLCM (Linder et al., 2017, 2020)	x		x (rem.)	x			
MCI (EMF & Granta, 2019)	x			x	x	x	
Circ(T) (Pauliuk et al., 2017)	x	x	x	x	x	x	any strategy
VRE (Di Maio et al., 2017)	x	x	x	x	x	x	any strategy
SCI (Azevedo et al., 2017)	x	x		x			also: rethink (sharing)
CFF (Zampori & Pant, 2019)	x			x	x		“end-of-life”
PCI (Bracquené et al., 2020)	x			x	x		
UOR/FRS (Moraga et al., 2021)	x			x		x	also: disposal (incineration without recovery)

While the CFF will be used as part of the environmental LCA (noting its short-comings, see section 10.4), the evaluation is somewhat inconclusive as to which CE method to prioritise for further analysis in WP2. When looking at the overall score and at the compatibility with LC(S)A, MCI, PCI, PLCM, Longevity and UOR/FRS could deserve further consideration. While Circ(T) and VRE consider all CE strategies presented in Table 17, they had lower overall scores in the evaluations. In terms of minimum requirements, it needs to be noted that Circ(T) and VRE should in fact be excluded from further considerations. This is because the methodological description of the VRE indicator ranks worst in terms of transparency and reproducing it based on the available literature is not possible. It also ranks worst in terms of credibility. Circ(T) in turn is very data-intensive which does not lend itself to be operational.

Using constituents of the CFF to establish stand-alone CE indicators could be explored. A straightforward solution, for instance, could be to use the R1 and R2 parameters of the CFF, i.e., “proportion of material in the input to the production that has been recycled from a previous system” and “proportion of the material in the product that will be recycled (or reused) in a subsequent system”, respectively (see section 4.4.8.1 in Zampori & Pant, 2019), as individual stand-alone indicators. Given the implications this might have regarding databases and LCA software tools, respective ORIENTING partners should be consulted (i.e., Ecoinvent Association and

Pre Sustainability). Likewise, inspiration might be sought from the company-focused guidance provided by the tools CTI2.0 (WBCSD, 2021)[28] and Circulytics (EMF, 2019).

In general, it would be desirable to have CE indicators that measure the improvements in absolute terms (i.e., changes in terms of sustainability impacts) and not in relative terms (e.g. share of recycled material). This is because the goal should be to have less material consumed and less waste produced. Therefore, evaluating CE measures in environmental, social and economic terms needs to be the measuring rod.

11.2.3 How to integrate CE indicators into the ORIENTING's LCSA?

In terms of integration of CE indicators (note the suggestions regarding the functional unit and life cycle stages in section 11.2.1), there are two somewhat opposed arguments. First, CE measures are means not ends which calls for a treatment that is not on a par with the three pillars of sustainability. Second, in order to identify trade-offs with the latter, the CE indicator results need to be presented alongside with the sustainability indicators. Either way, an integration with any of the three dimensions environment, economic, social does not appear to be an option.

If CE indicators are presented alongside with the sustainability indicators, an important consideration concerns the implementation of the LCSA integration tool, acknowledging that CE indicators are not at par with sustainability indicators (i.e., environmental, social, economic). The LCSA integration tool should allow sufficient flexibility for the user to (transparently) reflect the his/her preferences regarding each of the indicators provided by the LCSA framework. If weighting was involved, a weighting at different levels would be valuable, such as the one proposed by Schenler et al. (2009). This way, the user could first assign relative importance at the highest level (i.e., environmental vs. social vs. economic vs. circular) and then relative importance to the individual indicators summarised under each of these four groups of indicators (e.g. climate change is more important than noise or child labour is more important to avoid than increasing minimum wages). Still another way forward could be to show environmental, social and economic indicators as one set of results and CE indicators as additional but separate information, highlighting their differing nature. The CE information could simply consist of statements of the CE measures realised for a given product.

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[28] Distinguishing indicators according to the modules "Close the Loop" (e.g. % circular inflow, % circular outflow, % water circularity and % renewable energy), "Optimize the Loop" (e.g. % critical material and % recovery type and onsite water circulation) and "Value the Loop" (e.g. Circular material productivity and CTI revenue).

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13 Annexes

13.1 Annex A: Ecodesign principles

13.1.1 Introduction

Two key ecodesign standards have been recently published: IEC 62430:2019 and ISO 14006:2020. IEC 62430:2019 is focused on environmentally conscious design (ecodesign) at the design and development stage and built on IEC 62430:2009 that provided guidance for the electronics sector; through collaboration with ISO – as a double logo - this broadened the scope to cover all products/all sectors. ISO 14006:2020 is focused on how ecodesign (environmentally conscious design) can be incorporated and align to environmental management systems ISO 14001:2015 and quality management systems (ISO 9000:2015); the standard is focused on all products/all sectors. Neither of these standards explicitly referred to Circular Economy and/or product circularity strategies but a number of these strategies are implicit in the broader approach of ecodesign/environmentally conscious design (ECD).

Although the terms used within the standards are different the definition and core principles are the same. The reason is that IEC 62430:2019 builds on IEC 62430:2009 where ECD was used and ecodesign is the term used in ISO.

As IEC 6430: 2019 is more explicitly focused on design and development at a product level and below illustrates that lifecycle thinking is the backbone of ECD (ecodesign). For more detailed information, it is suggested that the standard is reviewed specifically.

IEC 62430: 2019 - Environmentally conscious design (ECD) — Principles, requirements and guidance: key clauses related to lifecycle thinking and product circularity

4 Principles of environmentally conscious design (ECD)

4.1 General

The application of the following principles is fundamental to implement ECD:

- life cycle thinking;
- ECD as a policy of the organization.

4.2 Life cycle thinking

Life cycle thinking includes, but is not limited to, the following elements:

a. having an objective to reduce the overall adverse environmental impacts of the product while still taking into account other aspects such as safety, quality;
b. identifying the significant environmental aspects of the product;
c. considering the trade-offs between different environmental aspects between life cycle stages

In order to include life cycle thinking within ECD, the above elements are considered as early as possible in the design and development, since that is when the greatest opportunities exist to make improvements to the product and to reduce any consequential adverse environmental impact.

Source: IEC 62430:2109

Annex A in the IEC 62430:2109 provides examples of how to apply ECD. Annex B provides information on how to select methods and tools for ECD (ecodesign) including in B.2.5 LCT based assessment.

Annex A1 illustrates that despite product circularity strategies not being explicitly mentioned in A1.2 Inputs and Outputs, there are mentions of implicit product circularity considerations in A.1.8 Maintenance, repair, upgrade, reuse and remanufacture. In A.1.9, End of life treatment and final disposal, there is a small reference to product circularity considerations "it should, consistent with stakeholders' requirements, be ensured that the used materials can be recycled and parts reused." In A.2 Examples of ECD strategies illustrates ECD (ecodesign) strategies that are open to product designers and developers including specific product circularity strategies and gives examples of general ECD objectives e.g. reduce weight by y kg. It should be noted, that the terms covering measurement, indicators or metrics are not used in the standard.

Table A1 in IEC 62430:2019 entitled "Examples of product-related environmental improvement strategies" provides examples of strategies for improving a product's environmental performance throughout the life cycle as part of ECD. These include various product circularity strategies that can be applied with ECD but these are not explicitly highlighted as such.

Table 18 illustrates product circularity strategies that companies might apply within ECD or ecodesign strategies.

Table 18: Generic eco-design checklist that features product circularity considerations in *italics* (non- exhaustive) with possible ways to consider the options in a LCSA context

Design Focus Area	Options for Design Improvement	Ways in which these options could be considered in a LCSA context
Design for Material Sourcing	*Reduce weight and volume of product*	As an indicator, using the weight and/or volume of a product.
	Increase use of recycled materials to replace virgin materials	Potential indicators: percentage (relative to total weight) or amount of recycled or virgin material
	Increase use of renewable materials	Potential indicator: percentage of renewable material
	Increase incorporation of used components	Potential indicator: number of re-used components
	Eliminate hazardous substances	Potential indicator: amount of hazardous substances (note however that there are the impact categories toxicity, ecotoxicity and ionising radiation whose score gives an indication on the amount of hazardous substances present in a product)
	Use materials with lower embodied energy and/or water	In LCA, we regularly assess the cumulative energy demand, sometimes even split into different

Design Focus Area	Options for Design Improvement	Ways in which these options could be considered in a LCSA context
		sources of energy. The same goes for the amount of water used.
Design for Manufacture/Assembly	Reduce energy consumption	See above (energy is part of LCA)
	Reduce water consumption	See above (water is part of LCA)
	Reduce process waste	In LCA, waste is regularly assessed. We should check how complete this is and which impact categories exist, though.
	Use internally recovered or recycled materials from process waste	No suggestion how to integrate this in LCSA for now; there could be dedicated indictors for it, but care needs to be taken regarding the proliferation of indicators
	Reduce emissions to air, water and soil during manufacture	In LCA, we quantify any releases (i.e., into air, water or soil). Given that one cannot directly add all those releases, however, these are afterwards converted into impact categories. When distinguishing the life cycle into different stages, one can distinguish the impact category indicator results of the manufacturing stage from the other stages.
	Reduce number of parts	No suggestion how to integrate this in LCSA for now; there could be dedicated indictors for it, but care needs to be taken regarding the proliferation of indicators
Design for Transport and Distribution	*Minimise product size and weight*	See above
	Optimise shape and volume for maximum packaging density	Very much related to the line just above and maybe too special to be dealt with separately in the LCSA.
	Optimise transport and distribution in relation to fuel use and emissions	In LCA, we quantify all transports and notably their fuel use and related emissions. As mentioned above: given that one cannot directly add all those releases, however, these are afterwards converted into impact categories. When distinguishing the

Design Focus Area	Options for Design Improvement	Ways in which these options could be considered in a LCSA context
		life cycle into different stages, one can distinguish the impact category indicator results of the transportation stage from the other stages. Question: what does transportation and distribution refer to? Only after manufacturing until the point of sale? Or also any other transportation (i.e., raw materials' transport from the mine to the next processing step(s) until the manufacturing and also from the point of sale to the user etc.)?
	Optimise packaging to comply with regulation	Packaging is part of LCA.
	Reduce embodied energy and water in packaging	See line just above
	Increase use of recycled materials in packaging	Couldn't this be dealt with as part of overall recycled material use?
	Eliminate hazardous substances in packaging	See above
Design for Use (Including installation, maintenance and repair)	Reduce energy in use	See above (energy is part of LCA)
	Reduce water in use	See above (water is part of LCA)
	Increase access to spare parts	No suggestion how to integrate this in LCSA for now; there could be dedicated indictors for it, but care needs to be taken regarding the proliferation of indicators
	Maximise ease of maintenance	First: does this only refer to the maintenance of the product or also to machinery in the manufacturing etc.? Second: Maintenance should be part of any LCSA where relevant. It could be defined as a separate stage. However, this might lead to very many stages, with a risk of overdoing things.

Design Focus Area	Options for Design Improvement	Ways in which these options could be considered in a LCSA context
	Maximize ease of reuse and disassembly	No suggestion how to integrate this in LCSA for now; there could be dedicated indictors for it, but care needs to be taken regarding the proliferation of indicators
	Avoid design aspects detrimental to reuse	No suggestion how to integrate this in LCSA for now; there could be dedicated indictors for it, but care needs to be taken regarding the proliferation of indicators
	Reduce energy used in disassembly	See above (energy is part of LCA)
	Reduce water used in disassembly	See above (water is part of LCA)
	Reduce emissions to air, water and soil	See above (emissions are part of LCA)
	Eliminate potentially hazardous substances that can be released during use	See above (toxicity/ecotoxicity/ionising radiation are part of LCA)
	Maximize ease of materials recycling	No suggestion how to integrate this in LCSA for now; there could be dedicated indictors for it, but care needs to be taken regarding the proliferation of indicators
Design for End of Life	*Avoid design aspects detrimental to materials recycling*	No suggestion how to integrate this in LCSA for now; there could be dedicated indictors for it, but care needs to be taken regarding the proliferation of indicators
	Reduce amount of residual waste generated	See remark on waste above
	Reduce energy used in materials recycling	See above (energy is part of LCA)
	Reduce water used in materials recycling	See above (water is part of LCA)

Source: Adapted from Charter (2018a)

From the product-related environmental improvement strategies shown in Table A1, the environmental objectives are developed and measurement, metrics and indicators (although as highlighted above this is not included the standard). An example of product circularity objective might be reducing weight by y kg, etc.

However, as indicated earlier trade-offs may be encountered between different environmental aspects. For example, optimizing a product for weight reduction might negatively affect its recyclability.

13.1.2 Ecodesign

As highlighted above, 80% of product's environmental impact is determined at the design stage (Charter & Tischner, 2001). Therefore, designers have a potentially highly influential role at the design phase – however, they do not have free will and have to operate within external constraints e.g. legislation, standards, etc and also internal constraints e.g. cost, technical feasibility, etc. Figure 6 illustrates how the designers influence starts high and diminishes throughout the lifecycle, and also how cumulative environmental impacts increase throughout the lifecycle (BSI, 2017). This illustrates that if product circularity is not incorporated into ecodesign then environmental impacts will increase e.g. not design for dismantlability, etc is likely to lead to 1st life landfill at the "End of Life".

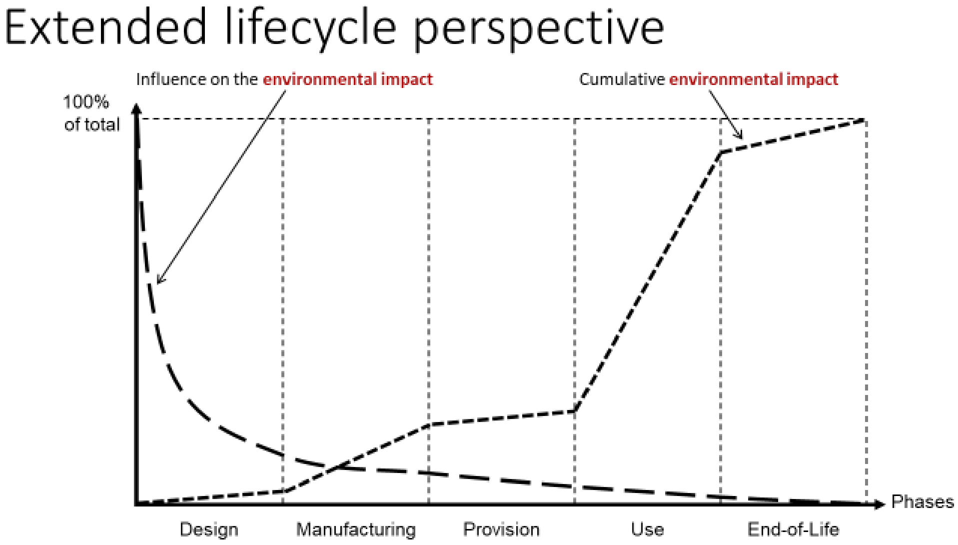

Figure 6: Extended lifecycle perspective (Source: BSI, 2017)

Figure 7 further elaborates the above bringing the notion of the Beginning-of-Life, Middle-of-Life and End-of-Life (Lindahl & Sundin, 2013). The Middle-of-Use phase is highlighted illustrating the nth life opportunities related to repair, refurbishment and remanufacturing of products. It also illustrates that at a specified time, products will come to the End-of-Use that then leads into the End-of-Life.

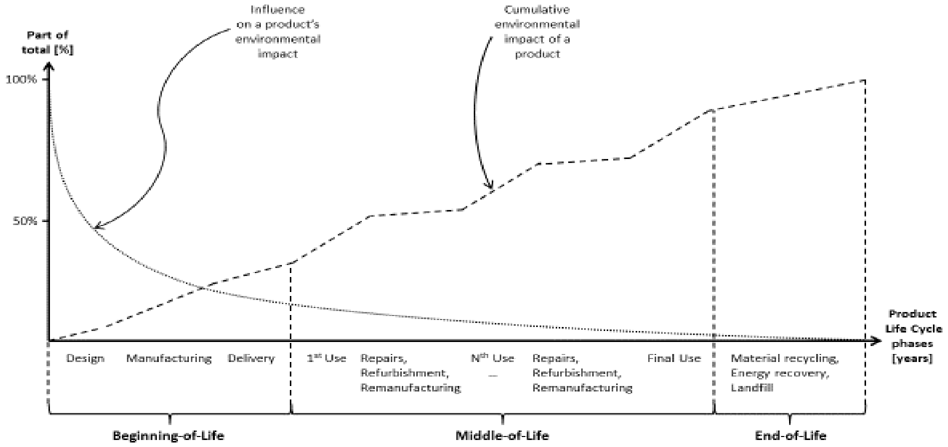

Figure 7: New perspective on product life (beginning, middle and end) (Source: Lindahl & Sundin, 2013)

Figure 8 further illustrates the material flows particularly related to remanufacturing (Johansson et al., 2019).

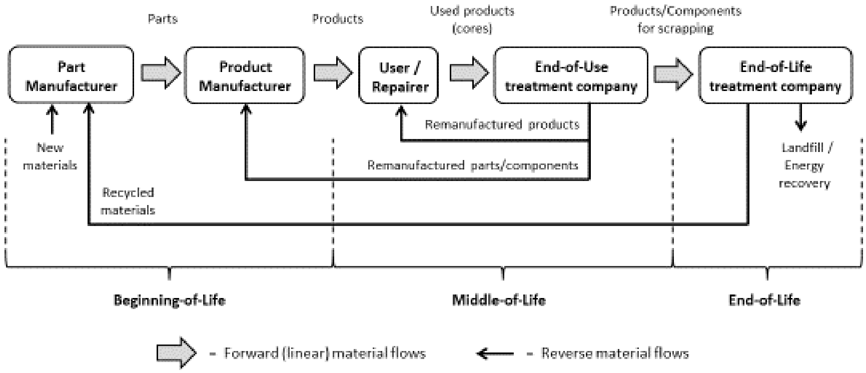

Figure 8: Materials flow related to remanufacturing (Source: Johansson et al., 2019)

13.1.3 Circular Product Design (CPD) or Circular Design (CD)

Circular Product Design (CPD) or Circular Design (CD) is a relatively new term that is not well defined, however the term is being increasing used. The term is primarily being in relation to product design and development, and primarily not in the sense of design and development to enable a Circular Economy (den Hollander et al., 2017). As mentioned earlier, CPD or CD should be seen as a specific part of ecodesign and not an end in itself. A singular focus on circularity is likely to lead to under-intended consequences especially if trade-offs are ignored. CPD, CD and circular business model (CBM) strategies (Charter & McLanaghan, 2018); Bocken et al., (2016) will receive growing attention as CE discussions increase but it is important not to forget the context e.g. CE sits within sustainable development as exemplified by the Sustainable Development Goals (SDGs) (Charter & Cheng, 2021).

Life cycle design emerged in the 1990s as an early approach to ecodesign. The concept was elaborated in The Life Cycle Design Strategy (LiDS) Wheel diagram (or Ecodesign Strategy Wheel) developed by researchers at Delft University of Technology which integrated the life cycle approach in relation to design and development improvement options (Brezet & van Hemel, 1997). LiDs proposed intervention in all life cycle phases of a product, in order to improve use of materials and energy, and provided a graphical representation of how product circularity or CPD strategies fitted within ecodesign. LiDs was followed by a range of other qualitative and quantitative life cycle design methods and assessment tools (United Nations Environment Programme, 1998, 2008, 2009) and further ecodesign tools and approaches (Charter & Tischner, 2001; Tischner, 2000). In the context of ecodesign, materials considerations were further elaborated in product design and development e.g. durability, reparability, upgradability, optimised energy and material consumption, and recyclability (Cooper, 1994, 2000, 2010).

The LiDs Wheel (or Ecodesign Strategy Wheel) includes eight strategies for product development: (I) selection of low impact materials, (II) reduction of materials usage, (III) optimisation of production techniques, (IV) optimisation of distribution systems, (V) reduction of impact during use, (VI) optimisation of initial lifetime, (VII) optimisation of End of Life system, and (VIII) new concept development.

Referring back to the table on product circularity consideration neither BS8001:2017 or PD CLC/TR 45550:2020 (CEN, 2020) explicitly consider products in the context of Technical Cycles and Biological Cycles related to the Circular Economy. As indicated previously, the same is true within both ISO14006:2019 and IEC 62430:2020.

Mestre & Cooper proposed a useful framework based on the LiDS Wheel that helps think through some of the issues related to “Design(ing) for a Technical Cycle” and “Design(ing) for a Biological Cycle” (Mestre & Cooper, 2017). Each is subdivided into two additional strategies creating four strategies to be considered within the different phases of the life cycle of a product. Technical (see Table 19): “design strategies to slow resource loops” (e.g. designing long-life products, and design for product-life extension) and “design strategies to close resource loops” (e.g. design for a technological cycle, design for a biological cycle, and design for disassembly and reassembly) (Bocken et al., 2016); and Biological (see Table 20): “bio-inspired loop strategies” and “bio-based loop strategies”.

Table 19: Life cycle design strategies to slow the loop and to close the loop – Technical Cycle

Life cycle design Strategies	Slow the loop	Close the loop
1 – Selection of low impact materials	a. Cleaner materials b. Renewable materials c. Lower energy materials d. Recyclable materials	a. Recycled materials b. Recyclable materials c. Biodegradable materials d. Lower energy materials e. Photodegradable materials f. Renewable materials g. Cleaner materials
2 – Reduction of material use	a. Reduction in weight b. Reduction in volume (transport)	a. Reduction in weight b. Reduction in volume (transport)
3 – Optimisation of production techniques	a. Alternative production techniques b. Fewer production steps c. Lower/cleaner energy consumption d. Less production waste	a. Alternative (optimised) production techniques b. Fewer production steps c. Lower/cleaner energy consumption d. Minimal production waste e. Fewer/cleaner production consumables

Life cycle design Strategies	Slow the loop	Close the loop
	e. Fewer/cleaner production consumables	f. Renewable material & energy resources g. Industrial symbiosis
4 – Optimisation of distribution system	a. Less/cleaner/reusable packaging b. Energy-efficient transport mode c. Energy-efficient logistics	a. Less/reusable/ biodegradable (zero waste) packaging b. Energy-efficient transport mode c. Clean & efficient energy logistics d. Elimination of logistics– "do it yourself" (e.g. 3D print at home with starch-based polymers)
5 – Reduction of impact during use	a. Lower energy consumption b. Cleaner energy source c. Cleaner consumables d. Fewer consumables needed e. No waste of energy/ consumables	a. Lower energy consumption b. Clean energy source c. Clean consumables d. Fewer consumables needed e. No waste of energy/ consumables f. Function as service (not product) g. Upgradability (modularity)
6 – Optimisation of initial lifetime	a. Reliability & durability b. Easier maintenance & repair c. Upgradability & adaptability d. Standardization & compatibility e. Modular product structure f. Dis- and reassembly g. Classic design h. Strong product-user relation (e.g. emotionally durable design)	a. Reliability & durability b. Easy maintenance & repair c. Upgradability & adaptability d. Standardisation & compatibility e. Modular product structure f. Dis- and reassembly g. Classic design h. Strong product-user relation i. Service for function maintenance (i.e., company takes back end-of-life product, replaces with new)
7 – Optimisation of End of Life system	a. Reuse of product b. Remanufacturing/ refurbishing c. Recycling of materials d. Safer incineration	a. Biodegradability b. Remanufacturing/ refurbishing c. Recycling of materials d. Recollection of product for dismantling/material extraction e. Compostability f. Nutritional value (waste=food)

Life cycle design Strategies	Slow the loop	Close the loop
		g. Photodegradation h. Reuse of product i. Repurpose of product function j. Recollection system for product
@ – Development of new concepts / Product design review / Other design concepts	a. Dematerialisation b. Shared use of the product (ownership) c. Integration of function d. Functional optimisation of product (components)	a. Dematerialisation b. Shared use of product (ownership) c. Integration of function d. Functional optimisation of product (components) e. Function as service (not product) f. Circular business model

Source: Mestre & Cooper (2017)

Table 20: Life cycle design strategies for bio inspired loop and for bio-based loop – Biological Cycle

Life cycle design strategies	Bio inspired loop	Bio based loop
1 – Selection of low impact materials	a. Bio materials b. Recyclable materials c. Clean materials d. Biodegradable materials e. Photodegradable materials	a. Renewable materials b. Biodegradable materials c. Compostable materials d. Clean materials e. Bio materials f. Photodegradable materials
2 – Reduction of material use	a. Biomimicry & bionics (biological structures) b. Reduction in weight c. Reduction in volume	a. Reduction in weight (less material = less pressure on biological life) b. Reduction in volume (transport)
3 – Optimisation of production techniques	a. Alternative production techniques b. Lower/cleaner energy consumption c. Less production waste d. Fewer/cleaner production consumables e. Industrial symbiosis	a. Alternative production techniques b. Lower/cleaner energy consumption c. Cultivation d. Fewer/cleaner production consumables
4 – Optimisation of Distribution System	a. Less/cleaner/reusable packaging b. Energy-efficient transport mode	a. Bio material packaging b. Energy-efficient transport mode

Life cycle design strategies	Bio inspired loop	Bio based loop
		c. Efficient distribution logistics – "grow it yourself" (e.g. mycelium - grow organism at home) d. Elimination of logistics – "do it yourself" (e.g. 3D print in house with starch-based polymers; cultivate material over structure in house; moulding bio waste materials etc.)
5 – Reduction of impact during use	a. Lower energy consumption b. Clean energy source c. Cleaner consumables	a. Clean energy source b. Clean consumables c. Fewer consumables needed d. No waste of energy/consumables
6 – Optimisation of initial lifetime	a. Biomimicry & bionics b. Dis- and reassembly c. Modular product structure (cell-like) d. Self-repair (e.g. self-sealing containers)	a. Reliability & durability (e.g. resistance to biodegradation before desired time) b. Easy maintenance & repair – e.g. self-repair & sustained growth (living materials)
7 – Optimisation of end-of-life system	a. Biodegradability b. Reuse of product c. Repurpose of product function	a. Biodegradability b. Compostable c. Solubility d. Nutritional value (waste=food) e. Compostability f. Photodegradation
@ – Development of new concepts / Product design review / Other design concepts	a. Biodegradability	a. Alternative (biological) production b. Shared cultivation of the material

Source: Mestre & Cooper (2017)

"Design(ing) for a Technical Cycle" is the transformation of material (and energy) resources through design optimisation to ensure the highest possible levels of efficiency. The aim is to minimise material (and energy) inputs, and emission outputs throughout the whole life cycle of a product, while maximising value in product, materials and components for as long as possible in economic and social systems (Charter, 2018b). Strategies for the technical cycle are "slow the loop strategies" and "close the loop strategies". "Slow the loop strategies" include slowing material flows in each phase of the life cycle such as design for durability and product life extension. "Close the loop strategies" include strategies such as design for recyclability that requires disassembly and appropriate materials selection. There are tensions between designing for durability and designing recyclability that need to be considered in the early phases of the ecodesign process within design and development and depend on decisions elated the product/market strategy related to individual types of products.

“Design for a Biological Cycle” represents the biological design solutions occurring in (or inspired) by the natural ecosystems, in which materials are cycled in nature over time (Benyus, 1997). Its biological composition aligns to the inherent efficiency of nature’s closed loop ecosystem (as opposed to the impact-minimising “Technical Cycle”). “Design for a Biological Cycle” consists of “bio-inspired loop strategies” and “bio-based loop strategies”. “Bio-inspired loop strategies” adopt a biomimetic approach that are long established and draw upon the science of bionics. “Bio-based loop strategies” aim to utilise biological materials that, at the end of their life cycles, can be returned safely to the biosphere in order to provide nutrients to (micro) biological life.

In the context of ORIENTING the strategies below might a useful contribution for the development of product circularity indicators and metrics.

13.1.4 Product circularity: Regeneration/Regenerating

The majority of product circularity strategies focus has been on retaining value and “adding value” as highlighted in section 7.2, Table 17, Table 19 and Table 20. There are a lack of highlighted product circularity strategies and definitions that focus on “design for regeneration”.

“Design for Regeneration” is a strategy that relates to materials processing and sourcing. As a first example, in the Technical System, regeneration is being used as term in relation to chemical recycling that enables depolymerisation and repolymerisation. Aquafil have developed Econyl - a brand of regenerated nylon fibres from fishing nets - that are used in clothing, carpets and other products (Econyl, 2021). As an second example, in the Biological System, relates agricultural practices related to the production of fibres and materials that is associated with Regenerative Agriculture (Regeneration International, 2021). The VF Corporation (that owns the brands Timberland, Vans and The North Face), is partnering with a Thailand-based design consultancy to create a regenerative rubber supply system to be used in footwear. Regenerative practices require the planting a variety of crops to preserve biodiversity and soil health; allowing animals to roam and graze as they would in “the wild”; rotating activities in line with the seasons and minimizing the use of pesticides. Allowing the soil to recover and different crops to grow, regenerative plots also sequester carbon. The regenerative rubber initiative builds on Timberlands Regenerative Leather footwear products initiative that includes regenerative leather with soles consisting of 75% renewable materials (a combination of sugar cane and natural rubber from trees) (Edie, 2021).

13.1.5 New thinking

In a paper, researchers at Delft University of Technology (den Hollander et al., 2017) consider guiding principles, design strategies and methods that would be required for products to be designed for a Circular Economy – which they term circular product design (CPD) - and to what extent these differ from the principles, strategies, and methods of ecodesign. The paper changes the focus from the micro level of designing products per se – ecodesign - (IEC 62430: 2019) to macro level of designing products for a Circular Economy (presently a hypothetical state). CPD is viewed as encompassing both design for product integrity (aimed at preventing and reversing obsolescence at a product and component level) and design for recycling (aimed at preventing and reversing obsolescence at a material level) (see Figure 9). Design for product integrity aims to preserve the product in its current form for as long as possible. The paper redefines *product lifetime – in terms of long use, extended use and recovery (see* Figure 10*)* - and highlights design strategies that are relevant for each of these three stages. The paper also introduces new terms such as *presource*, *recovery horizon, and design for recontexualising.*

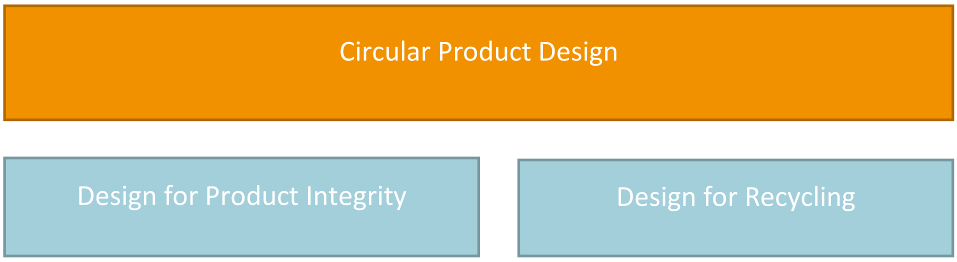

Figure 9: Circular product design, design for product integrity and design for recycling

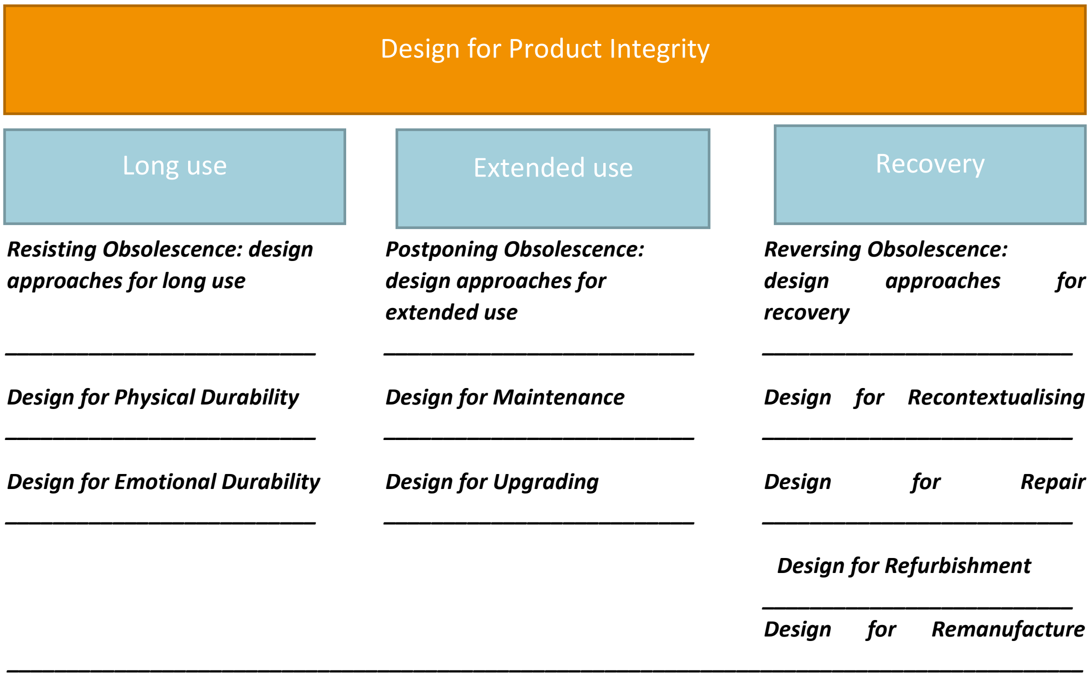

Figure 10: Typology of design approaches for product integrity (Source: den Hollander et al., 2017)

13.1.6 Ecodesign: an example

Philips are an example of advanced company in the application ecodesign and started their activities in the 1990s.[29] The company developed a series of tools based on Life Cycle Thinking to assess and help integrate environmental considerations into product design and development. As part of the application, at a product level, Philips developed a methodology called the six focal areas of ecodesign that they applied to both new products and redesign of existing products. Over the last few years, Philips have streamlined a couple of the focal areas and now circular is one focal area (see Figure 11). The company had goals to launch a number of "green" products per Business Unit and now have goals to launch "circular" products per Business Unit. Within the company there will be the development of circularity indicators and metrics in the absence of external standards. Philips have also recently put forward a proposal for a European Circular Ready Design standard within CEN/CENELEC.

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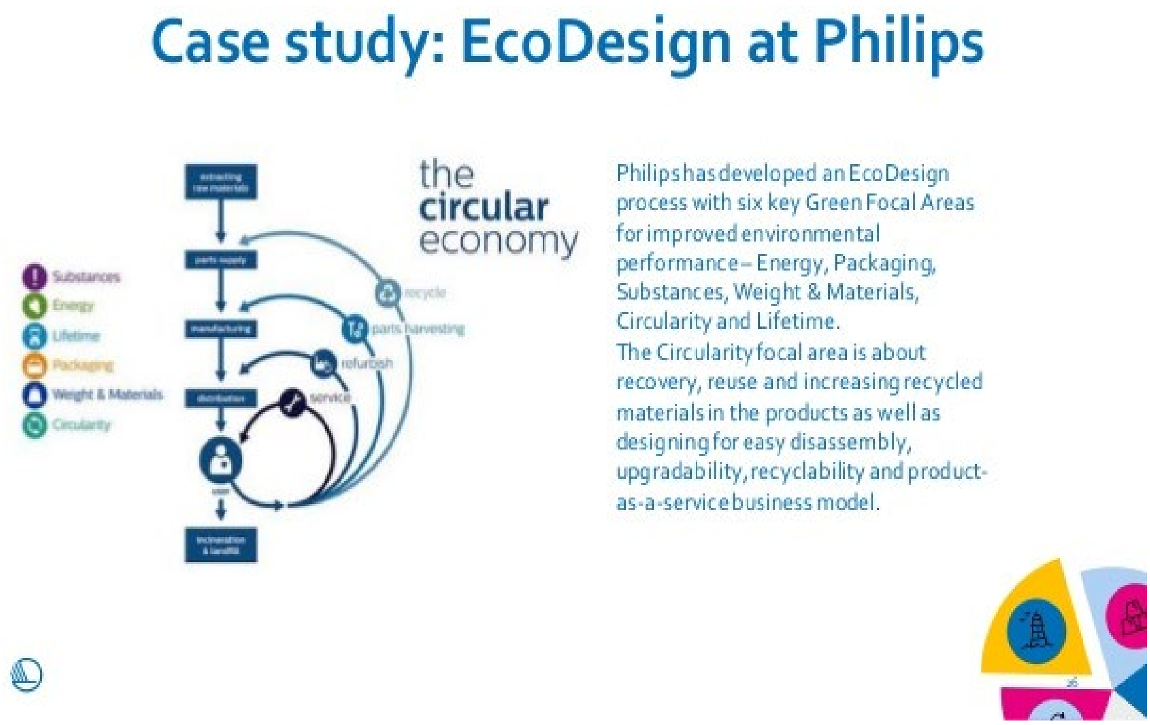
[29] Taken from deliverable 2 of the Prosum project (http://www.prosumproject.eu/, website accessed on 18 May 2021)



Case study: EcoDesign at Philips

Philips has developed an EcoDesign process with six key Green Focal Areas for improved environmental performance – Energy, Packaging, Substances, Weight & Materials, Circularity and Lifetime.

The Circularity focal area is about recovery, reuse and increasing recycled materials in the products as well as designing for easy disassembly, upgradability, recyclability and product-as-a-service business model.

Figure 11: Philips: Circularity is one component of its six focal areas of eco-design

13.2 Annex B: Detailed descriptions of analysed criticality methods

13.2.1 U.S. National Research Council (NRC)

This framework was developed by the U.S. National Research Council (National Research Council, 2008). It allows the assessment of supply risk and impacts of supply restrictions for minerals in a 2-dimensional space. For supply risk (x-axis), 5 different aspects of availability are considered (covering primary as well as secondary resources). The aspects vary depending on the assessment perspective (long, medium or short term). For impacts of supply restrictions (y-axis), a weighted composite score is used. The outcome of the methodology is the placement in a matrix, defining the degree of criticality. It assumes that criticality is best regarded as a continuum of possible degrees and not as a yes/no answer because it is context specific. It has been used for investigating the importance of non-fuel[30] minerals in the U.S., as for definition and identification of "critical" long- and short-term availability. The intended audiences are federal agencies, industry, research organizations, and decision makers. 11 mineral candidates have been evaluated within a case study. The perspective of the evaluation is strictly U.S. but can be adapted to other regions.

In contrast to other methods, there was no direct update of the approach by the NRC. However, the framework approach of a criticality matrix was accepted (and adapted) by other bodies (e.g. EU) and the work by the NRC was the basis for other criticality studies (e.g. Graedel et al., 2012).

13.2.2 European Commission Criticality Assessment - EU CRM list

The European ranking of Critical Raw Materials (CRM) was first published in 2011 and is updated regularly every three years (2014, 2017, 2020) (European Commission, 2017b, 2020c). It offers background data which can be used to evaluate the content material according to two dimensions, i.e., supply risk (SR) and economic importance (EI). The revised method from 2017 was developed with stakeholder involvement. The calculation of economic importance (EI) and supply risk (SR) is reported in the following equations:

$$\boldsymbol{EI} = \Sigma(\boldsymbol{A_s}*\boldsymbol{Q_s})*\boldsymbol{SI}_{EI}$$

Where

- EI is the economic importance;
- A_s is the share of end use of a raw material in a NACE Rev. 2 2-digit level sector
- Q_s is the NACE Rev. 2 2-digit level sector's Value Added;
- SI_{EI} is the substitution index (SI) of a raw material (in terms of economic importance);
- s denotes the sector

$$\boldsymbol{SR} = [(\boldsymbol{HHI}_{WGI,t})_{GS} \cdot \boldsymbol{IR}/2 + (\boldsymbol{HHI}_{WGI,t})_{EUsourcing}\ (1-\boldsymbol{IR}/2)] \cdot (1-\boldsymbol{EoL}_{RIR}) \cdot \boldsymbol{SI}_{SR}$$

Where

- SR is the supply risk
- HHI is the Herfindahl Hirschman Index (used as a proxy for country concentration)
- WGI is the scaled World Governance Index (used as a proxy for country governance)

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[30] "Nonfuel mineral" is used to distinguish oil and other energy minerals from yet further minerals.

- t is the trade adjustment (of WGI)
- IR stands for Import Reliance
- GS stands for global supply
- $EU_{sourcing}$ stands for the actual suppliers
- EoL_{RIR} is the End-of-Life Recycling Input Rate
- SI_{SR} is the Substitution Index (in terms of supply risk)

All calculations are based on data of the last 5 years as reference period. Materials crossing the threshold for supply risk as well as economic importance are ranked as “critical” and therefore listed as CRMs by the EC.

The approach is “non-forward looking” and therefore just a snapshot in time. According to the data used, the method is tailored to the EU.

13.2.3 Methodology of Metal Criticality Determination (or “Yale methodology”)

This methodology was published in 2012 and is an extension of work by the US NRC on Minerals, Critical Minerals, and the U.S. Economy (2008) (Graedel et al., 2012). The methodology aims at comprehensively determining the criticality of (individual) metals in the periodic system, mainly from a use perspective. It addresses three organizational levels (corporate, national, global), two time dimensions (medium- and long-term) and uses indicators for three dimensions (supply risk, environmental implications, vulnerability to supply restrictions). The results of the single indicators are aggregated to yield

a) a quantitative result per dimension (Quantitative scores (0-100 points) for each dimension, partly based on semi-quantitative or qualitative indicators) or
b) a single-score indicator (Single score indicator "criticality vector magnitude" available after aggregation and normalization).

Results are typically displayed in a 3-dimensional space to account for all 3 dimensions (supply risk, environmental implications, vulnerability to supply restrictions). Results are to be interpreted as a “snapshot in time”.

After its initial publication, the methodology has been extended to cover a wider range of elements, i.e., 62 metals and metalloids at national/global level (Graedel, Harper, Nassar, Nuss, et al., 2015). Further applications by other authors relate to water criticality at global level (Sonderegger et al., 2015) or construction aggregates at local/regional level (Ioannidou et al., 2017).

13.2.4 ESSENZ

The ESSENZ method has been developed at TU Berlin and builds upon the preceding ESP method (Bach et al., 2016a, 2016b). In addition to five environmental impacts (i.e., climate change, eutrophication, acidification, ozone layer depletion and smog) and abiotic resource depletion (classified to belong to the economic dimension) assessed according to standard LCIA procedures as well as two social indicators regarding acceptance (i.e., Compliance with environmental standards and Compliance with environmental standards), ESSENZ quantifies eleven geopolitical and socioeconomic accessibility constraints (country concentration of reserves and mine production, price variation, co-production, political stability, demand growth, feasibility of exploration projects, company concentration, primary material use, mining capacity, and trade barriers). Indicators for these categories are determined and divided by a target value above which accessibility constraints are assumed to occur. This distance-to-target (DtT) ratio is normalized by the global production of the respective resource to reflect the assumption that the accessibility constraints described above can be more severe for resources produced in relatively small amounts. Finally, the normalized DtT factors are scaled (to a range between 0 and the highest global production value among the considered materials, here 1.73×10^{13} in each category) using the rule of three to balance the influence of the LCI and the CFs on the LCIA result and to ensure a similar range of CFs among the supply risk categories.

The results are presented in 19 categories, a single score calculation is possible but not recommended. While 11 indicators are related to socio-economic availability and thus are relevant for criticality, eight indicators are based on LCA and two focus on social implications.

The target group are small and medium-sized enterprises as well as large companies that want to assess the resource efficiency of their product portfolio. The determined resource efficiency potentials should only be communicated to customers with regard to the so called “environmental impact” dimension. For the two other sub-dimensions “physical and socio-economic availability” as well as for the dimension “social acceptance”, communication to the outside world is not planned.

The method was developed in a consortium with strong industrial participation and is one of the interim recommendation of Phase 2 of GLAM for criticality (UNEP, 2019a).

13.2.5 British Geological Survey - Supply Risk Index

The methodology for estimating the relative risk of supply of a chemical element from 2015 is an updated risk list by the British Geological Survey and provides a simple indication of the relative supply risk of 41 elements or element groups (Shaw, 2015). A similar assessment has been carried out in 2011 and 2012. The position of an element on this list is determined by a number of factors that might affect availability. The score for the relative risk of supply is calculated based on seven criteria, each of them scored between one (low contribution to supply risk) and three (high contribution to supply risk), namely: Production Concentration, Reserve Distribution, Recycling Rate, Substitutability, Governance (top producing nation), Governance (top reserve-hosting nation), and Companion Metal Fraction. The score of each criterion is summed up to obtain the overall score for the risk of supply. Equal weight is given to each criterion. Finally, the aggregate score is normalized to have a simple supply risk index from one (very low risk) to ten (very high risk). Scarcity (previously based on crustal abundance figures) has been removed in the 2015 version. With the exception of substitutability, the list focuses on risks to supply and does not include any assessment of factors that influence demand, such as criticality of an element to a particular technology. The risk list provides policy-makers, industries and consumers with an indication of which element might be subject to supply disruption, most likely resulting from non-geological factors like geopolitics along with other factors like labour strikes, accidents and infrastructure availability. The goal is to ensure diversified supply of primary resources, to make full use of secondary resources and recycling and to reduce the intensity of resource use.

The analysis is a first approach to highlight some dependency issues. Further specification to the individual circumstances, unique to each metal and each country, in order to produce an effectual conclusion is needed (Strategic Metal Investments Ltd., 2011). Future issues are not taken into account; some mineral market aspects may change with time, and so will the results.

13.2.6 NEDO (Japan’s criticality assessment)

The method was developed by the New Energy and Industrial Technology Development Organization (NEDO) – Japan’s largest public management organization promoting research and development as well as deployment of industrial, energy and environmental technologies (Hatayama & Tahara, 2015).

The methodology is used to evaluate “strategic minerals” for Japan. Although the assessment report does not use the terms criticality or critical metal/material, the assessment evaluates the critical metals for Japan (Hatayama & Tahara, 2015).

The method evaluates five risk categories, covering 12 indicators in total:

1. Supply risk: depletion time, concentration of reserves, concentration of ore production, and concentration of import trading partners.
2. Price risk: price change and price variation.
3. Demand risk: mine production change, domestic demand growth, and domestic demand growth for specific uses.
4. Recycling restriction: stockpiles and recyclability.
5. Potential risk: possibility of usage restrictions.

The 12 indicators are normalized and can assume the values 0, 1, 2, or 3 (“points"). Based on these values, the indicators are aggregated into a single criticality score using weighting factors - 25% for each of supply risk, price risk, and demand risk category, 20% for recycling restriction, and 5% for potential risk (equal weights are used for all indicators of the same risk category). The calculated criticality scores can reach a maximum score of 32 points. Minerals with 18 points or more are classified as “strategic”. The indicators can be visualized individually in absolute values and the final criticality scores consist of a single integrated index.

The assessment is focused on minerals. It includes recycled materials through the recyclability index. The intended audience are all industry sectors with high import dependency for materials as well as policy-makers. Hatayama et al. (2015) propose an additional indicator to be included in the Supply Risk category: the sufficiency of mineral interest. This adds 3 additional points to the maximum criticality score.

13.2.7 GeoPolRisk

The Geopolitical Supply Risk (GeoPolRisk) assessment is focused on raw materials (Gemechu et al., 2017). It analyses mining/extracting and processing/refining stages. It also includes recycled materials, or secondary raw materials, through the recyclability index. However, it aims to provide information at a component/product production level. The intended audience is all industry sectors, policymakers and LCA practitioners (Gemechu et al., 2017).

In 2016, Gemechu et al. (2016) proposed an import-based indicator for the GeoPolRisk assessment of resources in order to add a supply risk perspective under the LCSA framework. The method builds on a number of previous criticality assessment methods, namely NRC (2008), Graedel et al. (2012); EC (2014b); Erdmann and Graedel (2011) and Achzet and Helbig (2013). The method is based on the Herfindahl-Hirschman Index (HHI) and the World Bank’s Worldwide Governance Indicators (WGI). Relying on these indicators and taking the perspective of the resource demanding country, it allows considering: the global share of a supplying-country in the production of a certain commodity, the geopolitical stability of this country and the import share of the demanding-country from the supplying-country. The only relationship of the original GeoPolRisk method with a typical LCI was the identification of resources, regardless of the volume of flows.

Helbig et al. (2016) advanced the method by adding more complexity to the supply-chain analysis. The proposal acknowledges that, for example, mining and processing of resources might not happen in the same country and that the relationship between the countries where these processes happen is also relevant. Cimprich et al. (2017) proposed additional improvements. The authors propose adding a vulnerability parameter that takes a material’s importance at the level of the whole economy and at product-level into account. The mass flows are now considered, analogous to LCI. Later, Cimprich et al. (2018) and Santillan-Saldivar et al. (2021) respectively proposed substitutability and the use of recycling rates as vulnerability-reducing parameters.

The GeoPolRisk method as proposed by Santillan-Saldivar et al. (2021) is calculated as follows:

$$GeoPolRisk_{APc} = m_{APc} {*} CF_{APc} = \frac{m_{APc} {*} GeoPol_{Ac} {*} s_{APc}}{m_{APc}} \qquad GeoPolRisk_{Ac} = HHI_A {*} \sum_i \frac{g_i {*} f_{Aic}}{p_{Ac} + F_{Ac}}$$

Where

- $GeoPolRisk_{APC}$ = geopolitical supply risk category indicator for commodity A needed to produce product P in country c
- m_{APC} = amount of commodity A needed to produce product P in country c
- CF_{APC} = geopolitical supply risk characterization factor for some commodity A needed to produce product P in country c
- $GeoPol_{AC}$ = geopolitical supply disruption probability for commodity A imported to country c
- s_{APC} = substitutability of Commodity A needed to produce product P in country c

The method is one of the interim recommendation of Phase 2 of GLAM for criticality (UNEP, 2019a).

13.3 Annex C: Detailed descriptions of analysed circularity methods

13.3.1 Product-Level Circularity Metric (PLCM)

The Product-Level Circularity Metric (PLCM, C-metric) was published by Linder et al. (2017). The quantitative method results in a single score indicator. The metric is not related to any other sustainability dimension.

The authors propose a new circularity metric based on the use of product parts' economic value (expressed as costs, readily available to producers) as a basis for aggregating recirculated and non-recirculated elements into a combined measure of product-related circularity. This is calculated by iteratively adding the economic values and circularity of product parts over the whole value chain. The metric can enable customers and producers to contribute systematically to an increased degree of material recirculation. On purpose, the authors sought to develop/design a metric that only deals with circularity (i.e., without including e.g. environmental impacts or the issue of material criticality). Two examples illustrate the applicability in the article in 2017. A more extensive list of examples can be found in Linder et al. (2020).

The methodology is focused on company level, while other interest groups are able to apply company-level metrics, too. Since publication in 2017, the article is cited over 110 times until the 8th of April 2021. Further a total of 14 Swedish firms applied the method (Linder et al., 2020). To run the methodology, around 15 person-hours are needed per product/company. The authors themselves note that the method might "be too difficult for most busy managers to apply on their own without at least some coaching" (Linder et al., 2020).

The calculations themselves could be done with MS Excel. To evaluate the method, specific company-internal data is needed. The indicator can be determined by the company itself. So, third-party access (or evaluation) is not necessary.

13.3.2 Material Circularity Indicator (MCI)

The Material Circularity Indicator (MCI) is an indicator for products and was proposed by the Ellen MacArthur Foundation in 2019 (EMF & Granta, 2019). The 2019 update also considers biological cycles. The quantitative method results in a single score indicator. The indicator is not related to any other sustainability dimension.

The MCI measures the extent to which linear flows have been minimized and restorative flows maximized for the component materials of a product, and how long and intensively it is used compared to a similar industry-average product. The result is a value between 0 and 1 where relatively higher values indicate a higher circularity. The calculation itself considers: the mass flows in the life cycle; timespan of usage (including durability of products, repair/ maintenance and shared consumption business models) and intensity of usage; rates and flows at the End of Life that are going to landfill (or energy recovery), collected for recycling and collected for reuse; the rates and flows of recyclable materials; composting and energy recovery from biological materials. The utility or function of the product is assessed in comparison to an average product of the same type. Therefore, some subjectivity for this step can be suspected. Data is mostly retrieved from companies. In addition, average data on the product analysed is needed as well. The MCI is intended for product analysis, but could also be used to build up a circularity profile for a company. The indicator targets the decision-makers at industries. The method concerns the product- or company-level and is widely known. It does not directly support policy-makers (Bracquené et al., 2020).

The methodology relies on similar values (mass and rates) as used by practitioners conducting LCA and criticality assessment. For these interest groups, the method is transparent and easily understandable.

13.3.3 Longevity

Published by Franklin-Johnson et al. (2016), the Longevity indicator is a quantitative method that results in a single score indicator. The indicator is not related to any other sustainability dimension.

The indicator measures the contribution to material retention based on the amount of time a resource is kept in use in a product system. The temporal calculation is measured in months. It includes initial lifetime (the total time of new material in use), earned refurbished lifetime (based on the refurbished or reused material - one or two times) and earned recycled lifetime (time that recycling adds to the lifetime of a material when used in a new product). Longevity is the sum of these three variables. The indicator is dedicated to evaluate products, including its components and materials. In the original study, the method was applied to mobile phones. The intended audience is the industry sector, but the method appears to be applicable for both company-specific product analysis and average product analysis (Saidani et al., 2019).

13.3.4 Circular Footprint Formula (CFF)

The Circular Footprint Formula (CFF) from Zampori and Pant (2019) is recommended by the European Union for dealing with materials and end-of-life allocation problems in LCA, in the context of the product environmental footprint (PEF). The method is quantitative and comprises three equations, i.e., one on material, one on energy and one on disposal (see section 4.4.8.1 in Zampori & Pant, 2019). Different from the other methods included in this evaluation, the result is not intended to be used stand-alone, although it could be used to build ad-hoc metrics. The formulae are rather used to allocate burdens and credits between suppliers and users of recycled (or reused) materials and recovered energy and to determine the environmental burden (releases and use of resources) of final disposal in landfills. It is generally applicable to final products and intermediate products.

13.3.5 Product Circularity Indicator (PCI)

The Product Circularity Indicator (PCI) is a further development of the Material Circularity Index (MCI, see section 13.3.2) from Ellen MacArthur Foundation (Bracquené et al., 2020). The quantitative method results in one indicator on product level and there are no overlaps regarding other sustainability fields.

The PCI gives a value between 0 and 1 where relatively higher values indicate a higher circularity. In Bracquené et al. (2020), it has been applied to washing machines as an illustration. The intended audience is not explicitly mentioned, but probably similar to the audience of the MCI indicator, i.e., decision-makers in industries.

The main differences between the PCI and the MCI can be summarized as follows:

1. The recycled content is defined at material level in the PCI, while, in the MCI, it is defined at product level.
2. Material losses during feedstock and component production are considered in the PCI. As a consequence, direct component reuse has more benefits compared to material recycling. This is a significant difference with the MCI method that only takes recycling efficiency into account.
3. In the PCI, material recovery and material recycling are considered to be fully part of the product system.
4. Material flow exchanges with the outer system boundaries are not accounted as fully circular in the PCI calculation method.

13.3.1 Circularity index (Circ(T))

Developed by Pauliuk et al. (2017), the circularity index Circ(T) method is quantitative and results in one indicator. The indicator itself does not overlap with other sustainability dimensions. Circ(T) is a performance indicator for the circularity of a material. It is defined as a relative measure of the cumulative mass of a material (e.g. steel) present in the system over a certain time interval in terms of an ideal reference case, where all material remains in functional applications throughout the entire accounting period. Circ(T) denotes the cumulative service provided by a material/product over a certain time span as a fraction of the maximal service possible (i.e., it is bounded by 0 and 1). Material loss and degradation are the two reasons why Circ(T) is smaller than 1 in all realistic cases. Similar to the global warming potential, Circ(T) varies depending on the chosen (reference) time horizon T. Circ(T) is a performance indicator for the circularity exemplified in a case study on by steel use throughout several life cycles (goal: maintain utility), that can be calculated from the based on scenario results of MaTrace Global, a multiregional extension of MaTrace (Nakamura et al., 2014) with global scope (Pauliuk et al., 2017). MaTrace Global is a supply-driven multiregional model of steel flows coupled to a dynamic stock model of steel use. According to different scenarios, annual results show how steel consumed in different countries are distributed across regions and products up to the year 2100. This can be used to analyse how current and anticipated technological options change the product distribution of steel in the future and reduce losses and thus improve circularity. MaTrace allows for tracing a certain unit of a recycled material through the supply chain. The model combines a dynamic stock model of the use phase of a material with a linear model of the waste management industries, the remelting processes, the manufacturing sectors, and the markets for End of Life products, i.e., scrap, secondary metals, and final products. The method is focused on single materials over multiple product cycles; only applied to steel so far.

13.3.2 Value-based resource efficiency (VRE)

Developed by Di Maio et al. (2017), the value-based resource efficiency (VRE) method is a quantitative method that results in a single score indicator. However, it also includes elements of other sustainability fields (criticality). The method proposes a new value-based indicator assessing the performance of actors in the supply chain in terms of resource efficiency and circular economy. The method measures both resource efficiency and circular economy in terms of the market value of so-called “stressed” [= scarce] resources. Di Maio et al. (2017) define circularity as “the percentage of the value of stressed resources incorporated in a service or product that is returned after its end-of-life” whereas “Resource efficiency is the ratio of added product value divided by the value of stressed resources used in production or a process thereof”.

13.3.3 Sustainable Circular Index (SCI)

The indicator Sustainable Circular Index (SCI) was developed by Azevedo et al. (2017). The quantitative method results in a single score result and embeds several indicators for circularity in a framework including other sustainability dimensions. In a five-phase framework, the SCI is calculated that is intended to be a benchmarking tool for manufacturing companies. The five stages are indicator selection, (Delphi based) weighting[31], normalisation, aggregation and index construction. Suggested indicators for circularity are “Input in production process” (virgin/recycled/reused), “Utility during use phase” (lifetime and lifecycles) and “Efficiency of recycling”. They are complemented by indicators for environmental, social and economic aspects. The intended application is to support decision making in manufacturing companies towards

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[31] The Delphi technique is used to obtain information from a panel of persons (e.g. experts).

circularity and sustainability. As it includes sustainability indicators, it overlaps with all three sustainability domains (Azevedo et al., 2017).

13.3.4 In-use occupation based indicators

In-use occupation based indicators was developed by Moraga et al. (2021). It is a quantitative method which results in two indicators and there is no overlapping to other sustainability fields.

The method comprises two newly developed indicators: in-use occupation ratio (UOR) and final retention in society (FRS). UOR is the percentage ratio between the in-use occupation along the product cycles and the theoretical maximum in-use occupation, that is, the performance of the entire occupation for the use of the material within the time horizon. The time duration of the time horizon is not fixed, the authors follow one of the temporal scopes proposed by the SUPRIM project (Sustainable Management of Primary Raw Materials). This project proposed three temporal scopes 5, 25, and >100 years (Schulze et al., 2020) . For measuring the circularity of a material in-use in the current generation and that can be available for future generation the Time horizon of 25 years was chosen. Additionally, the FRS shows the remaining percentage of the primary raw material at year 25. Two application cases are shown in the paper: a laptop; case and a wooden floor product (Moraga et al., 2021).

13.4 Annex D: Detailed results of the method evaluation against the T1.1 criteria

The detailed results of the criticality and circularity method evaluation can be found in the file D1.4 Criticality&Circularity Approaches Annex D.xlsx that can be accessed here: https://orienting.eu/documents-2/d14-criticality-circularity-approaches-annex-d/. The access to this MS Excel file is only possible for registered stakeholders.