Journal of Cleaner Production 102 (2015) 165–176

Contents lists available at ScienceDirect

Journal of Cleaner Production

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

Enhancing the practical implementation of life cycle sustainability assessment – proposal of a *Tiered approach*

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ARTICLE INFO

Article history:
Received 17 July 2014
Received in revised form
6 April 2015
Accepted 8 April 2015
Available online 25 April 2015

Keywords:
Life cycle sustainability assessment (LCSA)
Indicator selection
Tiered approach

ABSTRACT

Life cycle sustainability assessment has been claimed to be one of the most common methods for assessing sustainability of products and processes. It consists of the three methods life cycle assessment, life cycle costing and social life cycle assessment. However, the life cycle sustainability assessment framework is still under development and its application is still limited. This is substantiated not only by the lack of data and experience, but also by the proliferation of indicators provided by different institutions. Although indicators are available for the three sustainability dimensions, guidance for the indicator selection is missing. The bottleneck is not the lack of good indicators, but rather the lack of a clear indicator selection process. This appears to be one of the most crucial aspects as data availability, method development and interpretation of results heavily depend on this issue. Another obstacle for the practical implementation of life cycle sustainability assessment arises with the relatively high entrance level. Whereas, for the environmental dimension sufficient data and simplified methods are usually available, e.g. carbon footprint, the social and economic dimension are lacking of similar simplifications. Within this study a *Tiered approach* has been developed providing an indicator hierarchy and proposing a stepwise implementation concept. An indicator review has been performed according to the three criteria practicality, relevance and method robustness. Afterwards the indicators have been ranked in three tiers. The first tier ('sustainability footprint') focuses on indicators, which are characterized as easily applicable indicators and as relevant for production processes and on global scales. The second tier reflects current best practice indicators already used in case studies and preferred by institutions. The last tier aims at giving a comprehensive set of sustainability indicators, even if this level may not be applicable immediately. The Tiered approach may not solve all challenges within life cycle sustainability assessment, e.g. the question of how to solve the interpretation dilemma still remains; however it does support the practical application and further development of the framework through the stepwise implementation of sustainability indicators. The application and science related benefits of the Tiered approach result from the undergone comprehensive indicator review, which seems essential as a basis for further developments within the life cycle sustainability assessment framework, and from the proposed indicator hierarchy, which provides directions for further research. The created sustainability footprint facilitates the practical implementation of life cycle sustainability assessment, as the entrance barrier was lowered without neglecting any dimension of sustainability.

1. Introduction

Sustainability and Sustainable development have been important topics in today's societies since they were promoted by the Brundtland Commission in 1987 (United Nations, 1987) and even earlier within the 'Limits to growth' (Meadows et al., 1972; The Club of Rome, 2014) and 'A blueprint to Survival' (Goldsmith et al., 1972). Sustainable development (SD) is connected to all areas of human life, even though its definition has not been unified yet. There is an ongoing discussion about the delimitation of sustainability and sustainable development as well as the achievement of sustainable development. The terms are often used as synonyms even if sustainable development can be seen as a (policy) principle and central notion, which is openly defined as "development that meets the needs of the present generation without compromising the ability of future generations to meet their own needs" (United Nations,

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http://dx.doi.org/10.1016/j.jclepro.2015.04.053
0959-6526/

1987). On the contrary, sustainability is rather the property of a thing being sustainable (Heijungs et al., 2010).

Some argue that sustainable development rather follows the concept of weak sustainability (mostly in connection with the three-ring-model – addressing social, economic and environmental aspects), where trade-offs seem possible between the three dimensions (Giddings et al., 2002). Others by contrast state that SD goes beyond the weak sustainability concept via balancing the three dimensions (United Nations, 1987) and offers an attractive alternative to conventional growth-oriented development (Sneddon et al., 2006). Broad consensus has emerged about the contribution of social, environmental and economic aspects to sustainable development (Finkbeiner et al., 2010; Hacking and Guthrie, 2008; Heijungs et al., 2010). Additional dimensions, like cultural heritage or governance, are sometimes named, but have hardly been referred to within practical case studies. They also seem kind of irrelevant when focussing on the life cycle perspective, e.g. the proposed political-institutional (governmental) pillar is more related to organizations than to products (Burford et al., 2013). In addition, potential additional dimensions can often be covered within the social or economic dimension, e.g. cultural heritage has been mentioned as one possible pillar to measure sustainability (Burford et al., 2013), but has already been proposed as one impact category within the Guidelines of social life cycle assessment (Benoit and Mazijn, 2009). Hence, within this study the three common dimensions economy, environment and society have been selected to avoid diluting the assessment with too many side aspects (Hacking and Guthrie, 2008). The life cycle thinking concept plays an important role towards a practical implementation of sustainability aspects. Furthermore, a scientific life cycle based analysis is needed to avoid misuse of the term sustainable development (Heijungs et al., 2010). Therefore, within this study life cycle based sustainability assessment methods have been focused on.

Taking a closer look at the representation of sustainability aspects in practice it is conspicuous that most of the existing life cycle based methods still focus on only one of the three dimensions (e.g. life cycle assessment (Klöpffer and Grahl, 2014)) or are invalid from a methodological point of view (e.g. resource efficiency (Schneider et al., 2013)). However, with life cycle sustainability assessment (LCSA) a framework was established taking into account all three dimensions of sustainability, which is essential to display all resulting effects on sustainable development in a holistic way (Hacking and Guthrie, 2008). LCSA has also been promoted by the UNEP/SETAC life cycle initiative as a feasible framework to measure impacts on the three sustainability dimensions (UNEP, 2012; Valdivia et al., 2012). Within the following subsection the development and concept of life cycle sustainability assessment will be examined by pointing out the advantages and remaining challenges, which serves as a basis for the subsequent sections.

1.1. Life cycle sustainability assessment

The evolution of the LCSA framework has somehow been initiated with the development of the "Product Portfolio Analysis" (PROSA; German: Produktlinienanalyse) (Grießhammer et al., 2007; Öko-Institut, 1987). The PROSA approach was the first one considering three sustainability dimensions instead of one and can be seen as one of the initial ideas leading towards LCSA (Finkbeiner et al., 2010; Klöpffer, 2008). In addition, in the middle of the nineties the social and environmental life cycle assessment (SELCA) approach (O'Brien et al., 1996) was introduced referring to the three ring model similar to the one, which was later used within the LCSA framework. The current LCSA framework is still based on the three dimensions of sustainability economy, environment, and society and therefore takes up the structure of SD to a great extent (Giddings et al., 2002; Singh et al., 2012). It follows the triple bottom line of sustainability (Elkington, 1998) by integrating life cycle assessment (LCA) (Finkbeiner et al., 2006) to represent the environmental dimension, life cycle costing (LCC) to represent the economic dimension (Hunkeler et al., 2008) and social life cycle assessment (SLCA) to represent the social dimension (Benoit and Mazijn, 2009). Therefore, LCSA is clearly life cycle based (Klöpffer, 2008). Consequently, the three integrated methods LCA, LCC and SLCA have a similar modelling structure, following the life cycle of a certain product. The Guidelines of SLCA even state to follow the structure provided by ISO 14044, (2006) (Benoit and Mazijn, 2009). According to Swarr et al. (2011) similar accounts for LCC. Mainly this common ground was stressed to facilitate the definition and application of consistent system boundaries and functional unit for the three dimensions. However, the three methods have different target functions, which means they are looking at the same system from different perspectives (Heijungs et al., 2010; Wood and Hertwich, 2012).

The (theoretically) resulting advantage of LCSA is transparency, as it allows to identify trade-offs between the social, environmental and economic dimension (Heijungs et al., 2010). It is also often described as the most developed approach in terms of sustainability assessment (Zamagni et al., 2013). However, shortcomings exist, as LCA, LCC and SLCA do not have the same level of maturity, which hinders the broad implementation of LCSA. This is mainly substantiated by the evolutionary stage of the methods. Whereas, LCA is already a standardized method (ISO 14044, 2006) and widely used to investigate the potential environmental impacts of products and processes (Klöpffer and Grahl, 2014), LCC and SLCA are lacking of consensus and definition and thus broad practical implementation. SLCA assesses the potential social impacts of products and relates to the different stakeholder groups affected by the products, like workers, local communities and consumers (Benoit and Mazijn, 2009), but lacks proper impact assessment. LCC takes into account different perspectives (e.g. producer or consumer perspective) in order to consider the complete life cycle of a product (Hunkeler et al., 2008; Wood and Hertwich, 2012), but no impact level has been defined yet.

For LCA already broad range of well-described impact indicators is available and a common structure orientating on cause-effect chains has been developed (e.g. by the CML (Guinée, 2002) or ReCiPe (Goedkoop et al., 2009) method). Furthermore, related databases have already been established, e.g. GaBi or ecoinvent (UNEP and SETAC, 2011).

In comparison, for SLCA several impact categories have been proposed (Benoit and Mazijn, 2009; Neugebauer et al., 2014; Weidema, 2006), but they are still under discussion, as related impact pathways are lacking and the focus has so far been on the representation of stakeholder groups without bridging the gap towards impact assessment (Neugebauer et al., 2014). In addition, social data are hard to gather. Existing databases are only available on a top-down country or sector level, e.g. the Social Hotspot Database[1] (SHDB, 2013).

For LCC, similar to LCA it is possible to identify economic hotspots, which can be valuable for the decision making process within LCSA (Jeswani et al., 2010). Practical application is however lacking due to inconsistent documentation of cost sources (Wood and Hertwich, 2012) and poor data quality (Gluch and Baumann, 2004), even though some authors stated earlier that LCC is on a relatively fast track towards a comprehensive implementation

[1] The SHDB displays risk factors instead of impacts, but it is so far the only available database directly associated to SLCA.

(Hunkeler and Rebitzer, 2005). Databases for LCC are so far not available, except for the building and construction sector (Agyapong-Kodua et al., 2011; European commission, 2007), but costs are partly included in existing LCA databases (e.g. the GaBi 6.0 database) or displayed by conventional management accounting systems (Heijungs et al., 2012).

As demonstrated, indicators for all the three dimensions are available, but lacking in completeness or implementation. With this regard, Niemeijer and de Groot (2008) concluded that the bottleneck for assessments is not the lack of good indicators or good science, but rather the lack of a clear indicator selection process. Further challenges emerge as sufficient data and data sources are sometimes not or just partly available (Finkbeiner et al., 2010). Consequently, practical case studies are mostly far from being complete, as they may not cover all three dimensions, may not include the complete life cycle of products, may neglect some impacts, or may not even state the relation between indicators and impacts (Bienge et al., 2009; Heijungs et al., 2012; Heller and Keoleian, 2003; Moriizumi et al., 2010). Therewith, the representation of results within LCSA can be seen as another challenge (Ingwersen et al., 2014), as the interpretation of gathered results for the three methods goes beyond the complexity of LCA studies (Cinelli et al., 2013). Therefore, trade-offs between the dimensions must be identified with the utmost care and results must be displayed separately for each dimension (Arcese et al., 2013; Hunkeler and Rebitzer, 2005; Valdivia et al., 2012; Zamagni et al., 2013).

As a result, just a few life cycle sustainability assessment (LCSA) studies have been established (e.g. Martínez-Blanco et al., 2014; Traverso et al., 2012). Some approaches have been proposed in order to simplify LCSA. Pesonen and Horn (2012) proposed the sustainability SWOT as a streamlined tool for LCSA, which tries to identify the strengths, weaknesses, opportunities and threats of a product or process. It fails in gathering meaningful results as no indicator selection has been given beyond brainstorming about hotspots along the supply chain. Moreover, hotspots and impacts cannot be identified in any case, as user's experience is lacking or occurring impacts are still unknown. Thus, rather than a simplified tool, guidance through the existing indicators for LCSA is needed to enhance practical implementation and to support a valid identification of impacts along a product's supply chain.

1.2. Followed approach within this study

As shown within Section 1.1, four main challenges result from the above mentioned topics in connection with the LCSA framework: selection of indicators, related data availability, related method developments, and the interpretation of the indicator results (Ingwersen et al., 2014; Niemeijer and de Groot, 2008). Furthermore, transparency regarding the selection of indicators is often lacking and thus identified measures may be questionable.

In addition, challenges, which arise for any scientific tool, may as well be valid for LCSA. Crucial here seems to be the construction of a science-based theory that also contains well recognizable aspects to avoid a standstill in improvement and implementation (Heijungs et al., 2010). This appears to be especially relevant for the social and economic dimension within LCSA, as no noteworthy progress has been made since the release of the Guidelines of SLCA (Benoit and Mazijn, 2009) and the Environmental LCC book (Hunkeler et al., 2008). Thus, ways of bridging theory and practice need to be developed. Finkbeiner et al. (2010) in this context already stated earlier that there is a need to lower the entry-level into LCSA to enhance its usage. Pesonen and Horn (2012) agree with this view and state that the complexity of existing methods are the main obstacles for industry decision makers to implement life cycle based methods for assessing sustainability.

Following this argumentation, the most crucial aspect appears to be the meaningful selection of indicators, as data availability, method development and interpretation of results heavily depend on it. Therefore, within the following section, LCSA indicators in general will be discussed, leading towards the development of a new approach introduced in Section 3, which provides general guidance for LCSA studies. The benefits and remaining challenges will then be discussed in Section 4 before the contribution to science and the further enhancement of LCSA will be pointed out in the conclusions.

2. Consideration of indicators for LCSA

Indicators in general are something representing the state of a certain aspect or effect, which are used to measure a progress towards a stated goal (Parris and Kates, 2003; Turnbull et al., 2010). Within life cycle based methods the stated goal is typically defined as an area of protection (AoP). The related indicators towards this stated goal can function as variables, parameters, measures, measurement endpoints or thresholds, but are normally extended beyond measurements or values (Heink and Kowarik, 2010). Niemeijer and de Groot (2008) collected different classifications and frameworks for defining indicators. Those classifications are quite diverse; nonetheless indicators have been mostly described as an instrument to measure a causal effect. Typically, for LCA and accordingly LCSA inventory, midpoint and endpoint indicators can be differentiated describing different stages along the cause-effect-chain.[2] Accordingly, inventory indicators may be characterized as simple variables (e.g. SO_2 emissions), whereas midpoint impact indicators may be seen as parameters in the environmental mechanism network (Bare et al., 2000), which however may not account for all midpoint impacts. Endpoint impact indicators then can be seen as measurement endpoints. All this implies that indicators should be measurable, (policy) relevant, universally applicable and analytically resilient. In particular, the last two points are challenging in connection with LCSA, having regards also to the issue of data availability.

Additional challenges arise, as the three methods used for the assessment of the three dimensions have a different degree of maturity (Valdivia et al., 2012). Identical accounts for the indicators that represent the three dimensions. Furthermore, the process related nature of indicators used within the three methods LCA, LCC and SLCA show tremendous differences. Whereas within LCA, indicators are almost solely of quantitative nature and well defined within characterization models, indicators within SLCA can be qualitative, semi-quantitative or quantitative. In addition, the path from inventory towards an impact indicator can either be pursued via midpoint indicators towards an endpoint impact or unlike LCA via subcategories towards a stakeholder impact category (Parent et al., 2010; Wu et al., 2014). Although, the Guidelines for SLCA (Benoit and Mazijn, 2009) in both cases stick to the term social impacts, Parent et al. (2010) proposed earlier to use social performance for the latter one. To ensure consistency with LCA and to avoid confusion in connection with the term social impact, within this study the first approach is followed, as it has already been

[2] Detailed definitions and descriptions for cause-effect chains or impact pathways has been described earlier by Bare et al., 2000; Jolliet et al., 2004; and Kristensen, 2004. Definitions for the terms midpoint and endpoint indicator can also be taken from this sources, as e.g. Bare et al., 2000 described midpoint as “a parameter in a cause-effect chain or network for a particular impact category that is between the inventory data and the category endpoints”.

presented by Neugebauer et al. (2014). For LCC, even though the indicators are solely quantitative similar to LCA, another problem occurs, as no impact levels have been defined, yet. A similar issue accounts for the AoPs representing LCA, SLCA and LCC. Whereas, AoPs have been defined for the environmental and social dimension, there are none for the economic dimension.

Ideally, indicators of life cycle based methods should cover the complete impact pathway; however practical implementation shows a different picture. Although, LCA can be seen as the most advanced method within the LCSA framework (see Section 1.1), controversial discussions are ongoing, whether the inclusion of midpoint or endpoint impacts is expedient (Hutchins and Sutherland, 2008). Midpoint impact indicators are mostly seen as scientifically valid and easier to measure, whereas endpoint impact indicators might be more feasible due to clearer results, even though they might have shortcomings in scientific background and validity. Bare et al. (2000) concludes that midpoints and endpoints should be considered in parallel to enable coverage of the complete life cycle, but it was admitted that especially for complex models, under which LCSA can be counted, endpoint indicators are challenging due to unclear interrelations along the impact pathways.

Midpoint indicators for LCA and SLCA may impact a variety of endpoints, e.g. damage to human health, even though concrete pathways are not necessarily characterized or known (Hutchins and Sutherland, 2008). For the economic dimension not even midpoint impacts are defined and thus the consideration of endpoint impacts for the other two dimensions would lead to insurmountable divides. Building on this argumentation, for this study, midpoint impact indicators are included for LCA and SLCA. For LCC costs are considered functioning as inventory indicators,[3] as no impact level has been defined, yet. The development of method related shortcomings in connection with indicators maturity is not part of this study. However, the consideration of impacts seems reasonable, as impact indicators in contrary to inventory indicators display the relative importance of emissions, circumstances or consequences resulting from certain actions, which have been characterized into a proxy at a proceeded stage of the cause-effect-chain (Vanclay, 2002).

Due to the above mentioned challenges resulting from the different maturity levels of the three methods (LCA, SLCA and LCC), inter-linkages between the sustainability dimensions are hard to quantify, even though inter-linkages between the three dimensions do exist. However, the authors hypothesize that those inter-linkages of impact indicators (and consequently sustainability dimensions) rather arise towards the endpoint (damage) level, e.g. climate change affects simultaneously the endpoints of health and ecosystem stability or working condition may influence health damages. For the Tiered approach these inter-linkages may be acceptable, as ‘only’ midpoint impact indicators are considered, which instead of damages describe a state along the impact pathway.

To identify available and meaningful indicators for performing LCSA case studies, a literature review is conducted, taking into account research done by different institutions dealing with LCSA, LCA, SLCA and LCC, as well as publications and case study results addressing new aspects within the LCSA framework. In considering the practical application of LCSA, the state of the three methods in terms of indicator availability matters. For LCA, numerous indicators have already been defined and implemented. Such are included in common impact categories, like climate change or acidification. Topics, which are in this context broadly addressed are: resource impacts, biodiversity, natural environment and exhaustible resources (Pennington et al., 2004; UN, 2007; UNEP, 2012). However, some indicators are still challenging or not even addressed, like biodiversity (Klöpffer, 2008). Nevertheless, a preselection of indicators and impact categories has been given by several institutions, e.g. UNEP or JRC (Jolliet et al., 2014; JRC, 2011; UNEP and SETAC, 2011). All the prevailing indicators are connected to the three AoPs of LCA: ecosystem quality (also listed as natural environment), resources (also named natural resources) and human health (Goedkoop et al., 2009; JRC, 2010a). Although, human health was originally located in LCA, it has often been represented within SLCA as well. Therefore, the AoP human health, which was further addressed by Hacking and Guthrie (2008) and UNEP (2012), within this study is attributed to SLCA to avoid double-counting and to ensure an analogous allocation of indicators to the respective dimension.

For SLCA some midpoint impact categories have been proposed, but within case studies it is rather focused on subcategories than on midpoint impacts (see e.g. Martínez-Blanco et al. (2014)). However, important topics, which are considered in most of the performed case studies, are workers or working condition (including also wage levels), and health (Hunkeler, 2006; Hutchins and Sutherland, 2008; Jørgensen, 2012; Norris, 2006; Parent et al., 2010; Weidema, 2006). Moreover, education, gender equality and diversity are often mentioned, but have not been comprehensively included into SLCA practice (Hutchins and Sutherland, 2008). The defined midpoint indicators for SLCA representing these topics are: working condition, fair wage, health and education (Benoit and Mazijn, 2009; Neugebauer et al., 2014; Weidema, 2006), but are also going beyond, by addressing e.g. human rights, safety and cultural heritage (Benoit and Mazijn, 2009). Addressing the often qualitative or semi-quantitative nature of social indicators, it is worth mentioning that the characterization into impact categories is especially challenging. The most common AoP for SLCA following the Guidelines for SLCA is social or human well-being (Benoit and Mazijn, 2009), which has been also reflected in connection with social justice, prosperity and poverty (Burford et al., 2013; Cinelli et al., 2013).

For LCC no distinction has been made in inventory, midpoint or endpoint indicators. Swarr et al. (2011) therefore stated that the aggregation of costs already provides a measure of the financial impact of the product. Heijungs et al. (2012) somewhat disagreed and stated that the economic dimension goes beyond pure costs. However, classical impact categories following a cause-effect-chain, as described earlier, have not been defined yet. Therefore, LCC indicators within this study are limited to costs representing an inventory indicator level. The focus according to Hunkeler et al. (2008) should be set on such costs, which are important to assess the economic performance of products and processes. Discussions are ongoing about the inclusion or exclusion of external costs, as double-counting may occur with impacts considered in LCA (Swarr et al., 2011). Klöpffer (2008) therefore stated: if external costs are expected to be decision relevant and comprise real money flows, they must be included. In addition, double-counting is also likely to occur, when costs gathered for the different perspectives are summed up, as the purchase price already includes costs for manufacturing and needed materials (Heijungs et al., 2012). Therefore, caution is needed, when displaying the results of the LCC, by either displaying the different perspectives separately or by accounting for the resulting benefits, which are included into the purchase price. The latter requires more transparency with regard to the calculation.

Addressing the above mentioned points within this section, but also earlier within Sections 1.1 and 1.2, it appears logical to the authors of this study that focus on certain indicators is needed to

[3] Inventory indicators express single issues, e.g. pure emission factors instead of emission equivalents or salaries without relating them to fair wages.

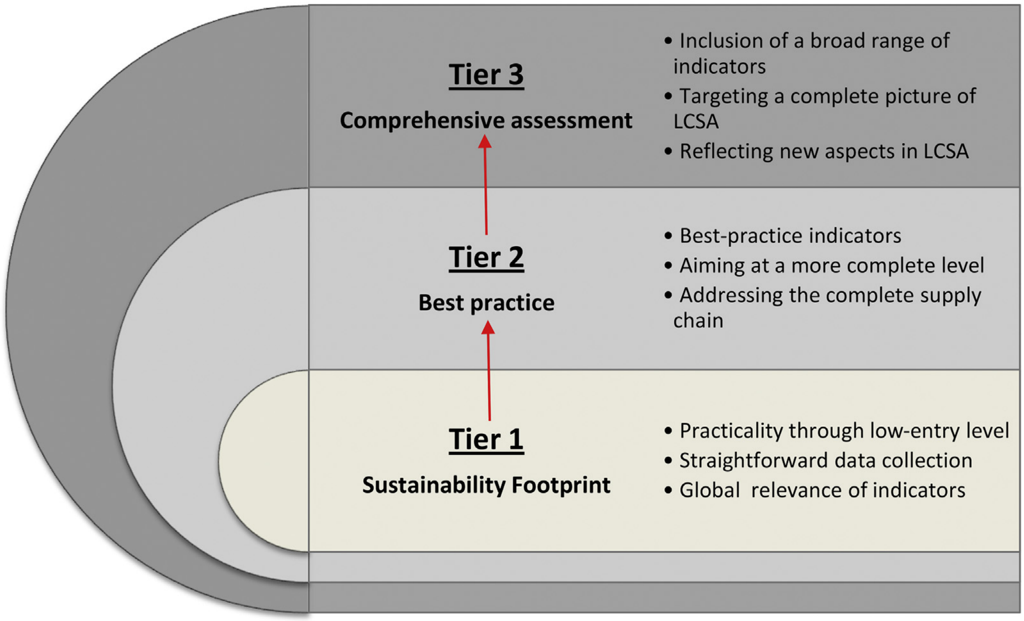

Fig. 1. Followed structure for the Tiered approach.

provide guidance and to aim at broader application and general improvements of the LCSA framework. This guidance is provided with the development of a new approach to ease the practical implementation of LCSA via including an indicator hierarchy. This *Tiered approach*, which functions as a stepwise technique through LCSA indicator implementation, is described in chapter 3. The related shortcomings and benefits when applying this approach are pointed out at the same time.

3. Tiered approach

The target of the developed Tiered approach is to enhance assessment practice towards a more holistic approach away from single dimension assessments. One assumption, which led to the development of the approach, is that assessments in any case subsist on continuity. In that sense, LCA and Carbon Footprint can serve as an example – popularity and propagation of the simplified Carbon Footprint method enhanced over time the more sophisticated LCA method in terms of practical application (Finkbeiner, 2009). Similar has been assumed during the development of the Tiered approach. By lowering the entry level and by giving an indicator hierarchy, LCSA will be simplified for the time being, to be then stepwise enhanced afterwards. Within the so-called 'sustainability footprint'[4] all three sustainability dimensions are considered from the very beginning, but just a limited number of indicators have been included (more detailed descriptions follow in the next paragraphs). Those indicators are preferably simple to implement. Afterwards, when the entrance barrier is surmounted a more comprehensive assessment is more likely to be established.

For an effective practical implementation of LCSA, three tiers have been defined starting with easy but meaningful indicators on *Tier 1* ('sustainability footprint'), proceeding with a state of the art set of indicators at *Tier 2* ('best practice') and concluding with a preferably comprehensive set of indicators measuring the sustainable performance at *Tier 3* ('comprehensive assessment') (see Fig. 1). It is assumed that the crucial obstacle for performing LCSA is the first step. Thus, after observing Tier 1 and 2 slowdowns in the implementation of additional indicators are founded in data availability or method insufficiencies, which are both difficult to overcome with increasing indicator complexity (e.g. climate change is due to data availability, public awareness and a mature method easier to assess than e.g. ecotoxicity). An additional subdivision in more than three tiers therefore seems not essential to perform LCSA in a more complete manner. Foremost, as additional indicators can be easily adapted in the provided scheme.

To be able to structure LCSA indicators into different tiers, a comprehensive research has been performed in advance, addressing the three dimensions and taking into account three key criteria to enable a reasonable indicator selection: relevance of the indicator, robustness of the related method, and practicality of the respective indicator. The criteria have been applied to a broad range of midpoint indicators for LCA, for all defined midpoint indicators for SLCA and for cost categories for LCC.[5] The criterion relevance displays the importance of the indicator for the respective method (LCA, SLCA, LCC) and the pressure behind the covered topic (Niemeijer and de Groot, 2008). Therefore, work done by international organizations and institutions has been considered. Method robustness describes the scientific dimension of the available characterization methods and their validity (see Niemeijer and de Groot (2008)). Practicality refers to data availability and the resulting societal responses. Thus, besides the awareness for the topic, also the conditions for the LCSA implementation have been considered. The indicators are ranked according to a scale of high, medium and low compliance for each of the three criteria. The

[4] In general a footprint can be described as a measure of how human activities create different kinds of burdens (Čuček et al., 2012). Outstretched on LCSA therefore the environmental, economic, and social dimension need to be included. However, it is focused on the principle followed by carbon footprint, water footprint and comparable methods, to include single indicators displaying a certain impact or problem.

[5] More information can be taken from the supplementary data. Within the supplementary data all indicators identified for the three dimensions are ranked according to method robustness, relevance and practicality. Sources are named. Further information, which is not in any detail represented in the text, can be taken from the related table.

Table 1
Proposed set of indicators for Tier 1 ('sustainability footprint') within the Tiered approach.

Indicators of Tier 1		
LCA	LCC	SLCA
Climate change *If agricultural products use Eutrophication in addition, as agricultural processes might be driven by phosphorus and nitrogen emissions (Tynkkynen et al., 2014; Velthof et al., 2014).	Production costs Including manufacturing, labour, energy, transportation & maintenance costs	Fair wages Comparison to minimum & non-poverty wage

analyzed set of indicators and the evaluation according to the three selection criteria is documented in any detail within the supplementary material.

Practicality has been rated as the most important criterion, as without it, application is unlikely. Consequently, practicality decreases from Tier 1 to Tier 3. This is not necessarily the case for method robustness or relevance. However, the general criteria fulfilment is also decreasing from Tier 1 to Tier 3, e.g. method robustness can only be considered, if a respective method is available, which is not necessarily the case for all social impact indicators considered. As least attention in terms of practical implementation and methodological progress has been paid to the LCC method, the related indicators are hardly covered within public discussions and no characterization models are available. Therefore, practicality frames the indicator selection for the three tiers (see supplementary data).

According to the ranking presented within the supplementary data, the LCSA indicators are assigned to the three tiers.[6] In addition, some further aspects are considered. For the social dimension the stakeholder groups, which were defined by the Guidelines of SLCA (Benoit and Mazijn, 2009), are considered, as one, two or all stakeholder groups might be affected by a certain impact. Similar accounts for LCC, where the different perspectives are taken into account to properly represent the (direct and indirect) costs occurring for the different stakeholders. For LCA no distinction in stakeholder groups or perspectives is needed. Generally, the descriptions for the environmental dimension are kept rather short, as for all indicators, characterization models have been defined and thus clear descriptions and definitions already exist.

3.1. Tier 1

Lowering the entrance level for LCSA and targeting applicability in the first tier of the Tiered approach, indicators with high practicality and good data availability are selected. As Tier 1 follows the idea of a 'sustainability footprint', well-known indicators are chosen to ease understanding also for non-expert practioners. For the environmental dimension the carbon footprint (midpoint category climate change or global warming potential) is included in Tier 1 (Table 1, column 1), which has become one of the most important environmental indicators, according to (Galli et al., 2012; Lam et al., 2010; Wiedmann and Minx, 2008). Several organizations identified climate change as relevant, e.g. IPCC Stocker et al. (2013), OECD (2008), WMO (2013) and UNEP (2014), and besides it is covered by the Kyoto protocol (United Nations, 1998). Consequently, the awareness and knowledge amongst stakeholder groups is supposed to be very high. The data obstacle is relatively little, as inventory data and characterization factors are widely available (Goedkoop et al., 2009; Guinée, 2002). Data and characterization factors have been implemented in common LCA software (e.g. GaBi 6.0) and carbon footprint calculators.

Although, climate change is of high relevance for utmost production processes and therefore is chosen as a generic Tier 1 environmental indicator, eutrophication might be in some cases of more relevance. For instance, agricultural processes might be driven by phosphorus and nitrogen emissions from fertilizer use (Tynkkynen et al., 2014; Velthof et al., 2014). Awareness in this context increases and eutrophication is verifiable of relevance, as it is one impact driver in agricultural production and also functions as an indication for biodiversity loss (Hodgson et al., 2014; Jolliet et al., 2014). Inventory data and characterization factors are also available (Goedkoop et al., 2009; Guinée, 2002).

For the LCC the literature according to Hunkeler et al. (2008) and Swarr et al. (2011) is followed and therefore material, manufacturing, labour, energy, transportation and maintenance costs are included in Tier 1. Accordingly, all direct production costs are covered within this tier. Heijungs et al. (2012) and Hochschorner and Noring (2011) with this regard stated that those costs are covered by the management accounting and Bovea and Vidal (2004) described them as conventional costs, which are easy to assess (Table 1, column 2).

One of the most applicable indicators considered within SLCA is Fair wage. It can be assessed by comparing the wage level of workers with minimum and non-poverty wages (e.g. Schulten (2014)) (Table 1, column 3). Fair wages are essential for satisfying workers basic needs to ensure stable living conditions (Benoît et al., 2013; Kenrick et al., 2010). Moreover, fair wages can be seen as the first step towards poverty alleviation (Worldbank, 2014), determining the time a person has to work to achieve food, housing and education (Klöpffer, 2008). Fair wage therefore describes perfectly a necessity to fulfil basic needs, as addressed earlier by Maslow with the pyramid of needs (Maslow, 1954, 1943). Data addressing wages are provided by i.a. World Bank and ILO. A first qualitative characterization model has been provided by Neugebauer et al. (2014).

Recapitulating, Tier 1 consists in total of three generic indicators representing the three dimensions within LCSA. All selected indicators are highly relevant for production processes in general, but can also be seen as crucial aspects for the related method (LCA, SLCA, LCC). However, the indicators may not be completely equal; therefore, results need to be displayed transparently and separately.

3.2. Tier 2

Reflecting the current best-practice, Tier 2 aims at including additional LCSA indicators. Indicators are included according to the suggestions of international institutions representing the state of the art for LCA, LCC and SLCA.

For LCA the recommendations of the International Reference Life Cycle Data System (ILCD) handbook are followed. Within this handbook different level of midpoint indicator maturity have been defined: level I – recommended and satisfactory; level II –

[6] The authors of this study strongly recommend the reader to take a look at the supplementary material, as a comprehensive overview of the LCSA indicators and explanation of the performed ranking have been pointed out in detail in accordance with the defined criteria.

Table 2
Proposed set of indicators for Tier 2 ('best practice') within the Tiered approach. Additional indicators compared to Tier 1 are highlighted in red.

Indicators of Tier 2		
LCA	**LCC**	**SLCA**
Climate Change	Production costs	Fair wage (comparison to non-poverty wage)
Ozone Depletion	*including manufacturing, labor, energy, transportation & maintenance costs*	*comparison to minimum & non-poverty wage*
Eutrophication	Consumer costs	Health (represented via Humantoxicity)
Photochemical oxidant formation	*including purchase prices, energy costs and costs of usage & maintenance costs*	*including health effects on workers, consumers and local communities*
Acidification		Working condition
Particulate matter		*including working hours and existence of labor laws*

recommended but in need of some improvements; level III – recommended but to be applied with caution (JRC, 2011). The set of indicators suggested for Tier 2 (Table 2, column 1) has been classified as level I and II. These indicators reflect the common best practice in LCA. Further justification for the implemented indicators can be taken from the supplementary data. All included indicators are covered within characterization models and have already been accepted within the LCA community (Jolliet et al., 2014; Pennington et al., 2004).

For the LCC further types of costs are included representing the consumers perspective. This includes purchase prices, costs for energy and usage, and maintenance (Table 2, column 2). Maintenance costs and costs of usage do not necessarily occur, but if so they need to be considered. The energy costs on the consumer side can be more difficult to assess, as they strongly depend on the user's behaviour and therefore scenario technique may need to be used.

For the social dimension additional indicators are included reflecting human health and working conditions (Table 2, column 3). Health has been broadly addressed within SLCA literature (see Section 2), within LCA literature (Jolliet et al., 2014) and by numerous institutions, like WHO or OECD. However, hardly any valid characterization method has been developed to consistently represent health issues within SLCA. Therefore, within this study it is mainly referred to Humantoxicity, wherefore a characterization method has already been provided within the Usetox model (Rosenbaum et al., 2008). In addition, direct health effects have generally been identified for workers, consumers and local communities and can therefore be relevant. Thus, whenever certain health effects are likely for specific products or processes, they should be at least qualitatively considered. Data sources, considering health issues, which go beyond toxicity, are additionally listed within the supplementary data.

Furthermore, the midpoint indicator Working condition is included in Tier 2, as numerous SLCA studies have already addressed this issue (see Section 2). It was further identified as relevant by ILO and World Bank and was represented by different trade unions. Dreyer et al. (2006) and Kruse et al. (2008) developed a first characterization model based on working hours. However, additionally to working time, compliance with labour laws is of importance to understand the prevailing circumstances, which are needed to achieve good working conditions (ILO, 2011). Data are available, but no characterization model has been provided with this regard.

To ensure delimitation of the two indicators health and working condition, which as an indicator may also affect health issues depending on the definition, health is mainly described by Humantoxicity at the midpoint level and working conditions are restricted to working hours and the existence of labour laws. Whereas inter-linkages are likely to occur at the endpoint level (e.g. both indicators may influence damages to human health), they are unlikely at the midpoint level, due to a clear demarcation (see also Section 2).

Subsuming, additional indicators have been included into Tier 2 to express a broader range of environmental aspects (e.g. ozone depletion or acidification), to give a more detailed picture about occurring costs (via the inclusion of consumer costs), and to express social impacts beyond the stakeholder group workers, which was mainly focused on within the 'sustainability footprint' (Tier 1). The resulting number of indicators for the three dimensions is uneven and different perspectives (LCC) and stakeholder groups (SLCA) have now been considered; thus it is of even greater importance than in Tier 1 that the LCA, LCC and SLCA results are displayed separately and transparently. However, a weighting of results does not seem necessary, as no quantitative comparison is performed, but rather a verbal argumentative discussion on the results. Therefore, the concrete number of indicators is not especially relevant at this stage.

3.3. Tier 3

Tier 3 aims at a comprehensive coverage of LCSA. Therefore, additional indicators are included (see Table 3); even though some indicators defined as midpoint impacts earlier are lacking proper characterization models and practical implementation. This accounts mainly for indicators of SLCA and especially LCC, but also for

Table 3
Proposed set of indicators for Tier 3 (best practice) within the Tiered approach. Additional indicators compared to Tier 2 are highlighted in red.

Indicators of Tier 3

LCA	LCC	SLCA
Climate Change	Production costs	Fair wage (comparison to non-poverty wage)
Ozone Depletion	*including manufacturing, labor, energy, transportation & maintenance costs*	*comparison to minimum & non-poverty wage*
Eutrophication	*including further operational cost, like waste management & taxes*	Health (represented via Humantoxicity)
Photochemical oxidant formation	*including capital, infrastructure, investment costs* *including costs due to accidents & environmental damage, if not included within LCA or SLCA*	*including health effects on workers, consumers and local communities*
Acidification		Working condition
Particulate matter	Consumer costs	*including working hours and existence of labor laws*
Ionizing radiation	*including purchase prices, energy costs and costs of usage & maintenance costs*	Education
Ecotoxicity	*including further operational cost, like waste management & taxes*	*including finished apprenticeships & university degrees, equal opportunities, literacy rate*
Land use	*including costs due to accidents & environmental damage, if not included within LCA or SLCA*	
Water footprint		Human rights
Resource depletion		*focus on workers & local communities* *including child labor, forced labor, discrimination, equity & autonomy*
		(Workplace) Safety
		Cultural heritage (in connection with local communities)

new methods of LCA like the water footprint method (Berger et al., 2014) (more information can be found in the supplementary data).

Within the LCA part, further indicators are added describing the state of the environment in a preferably holistic manner. This comprises midpoint indicators for ionizing radiation (JRC, 2010b), ecotoxicity (e.g. Rosenbaum et al., 2008), land use (e.g. Milà i Canals et al., 2007), water use and consumption expressed via water footprint methods, e.g. Berger et al. (2014), and resource consumption (Guinée, 2002) (Table 3, column 1). Characterization factors have already been provided, but are not always sufficient or complete (e.g. the provided characterization models for land use do not consider all relevant aspects). Impacts on biodiversity have not been directly included in the Tiered approach, as neither a characterization model has been established nor consensus has been achieved regarding its allocation to the midpoint or endpoint level (JRC, 2010b; UNEP, 2012).

The LCC is complemented by including remaining conventional costs, e.g. taxes and insurances. Further, costs for capital and infrastructure are added, which are needed to perform necessary production processes on the manufacturer's side. For capital and infrastructure costs the inclusion of discount rates was recommended by some authors, e.g. Dong et al. (2014) and therefore their inclusion might be challenging. In addition, indirect costs due to accidents or environmental damages are considered as far as the related impacts have not been reflected within the environmental or social dimension (Table 3, column 2). Hence, as long as accidents have not been covered in the social dimension e.g. in connection with health, but have already been expressed in economic terms, they should be included to ensure integrity of the LCSA model. The same accounts for the environmental damages, which have not been covered within the environmental dimension. These costs can occur on both the producer's and consumer's side; however it must be indicated clearly by whom these costs are paid. Data for these costs are partly available (e.g. capital and infrastructure costs), but the assessment of taxes and costs for accidents can be challenging, as they are not necessarily covered within management accounting systems.

For SLCA the indicators education, human rights, safety and cultural heritage are added for Tier 3 (Table 3, column 3). These indicators are typically seen as midpoint indicators, but hardly any of them have been expressed within characterization models (see also supplementary data). For education, a first characterization model has been proposed by Neugebauer et al. (2014), but no characterization factors were calculated. However, according to the provided qualitative characterization scheme, equal opportunities, literacy rate and finished degrees were focused on as a first proxy. Regardless of the current methodological shortcomings, education is of high relevance for (sustainable) development (Klöpffer, 2008; Weidema, 2006) and part of the Millennium development goals,[7] and should therefore be at least qualitatively considered within a comprehensive LCSA. Data on education are i.a. provided by ILO (2010), The World Bank (2013) and OECD (2013).

Human rights are normally expressed by different subtopics, e.g. child labour, forced labour, discrimination and equity. The topic was also often addressed within case studies (Hauschild et al., 2008; Jørgensen et al., 2009; Martínez-Blanco et al., 2014) and by several institutions, e.g. Human Rights Watch[8] and Amnesty International (1998). Nonetheless, only qualitative statements or risks have so far been evaluated, as a characterization model is missing. Qualitative data addressing the situation on human rights are provided by ILO, The World Bank and the United Nations. Moreover, human rights are hardly expressible in quantitative terms, but relevant violations of human rights should be named and listed transparently within the assessment of social impacts.

The defined social impact category safety has been mostly addressed with regard to workplaces and labour (Sakamoto, 2010; UNEP, 2010), but also in connection with food and poverty (Heller and Keoleian, 2003; UN, 2007). Nevertheless, no characterization model has been yet defined for safety and data sources are hardly provided by institutions. However, aspects on safety should be included as long as they have not been displayed within the midpoint indicator health. Further research is needed to determine, if safety shall remain as its own impact category or rather be included into working conditions and/or health.

Just a few institutions[9] addressed cultural heritage and even fewer case studies. The foremost reason for this is its limitation to local communities. Furthermore, impact definition lacks and the qualitative nature of the indicator impedes a straightforward inclusion into characterization models. However, background information has been provided by the Journal of Cultural Heritage and therefore the indicator is regarded for now within Tier 3 of the Tiered approach.

Similar can be even stronger presumed for the two indicators socio-economic repercussions and governance. Socio-economic repercussions was by literature only named in connection with climate change (IPPC), health and HIV/AIDS (Isaksen et al., 2002) and therefore should be rather included into the midpoint category health, than to be expressed in an own impact category. A clear definition is also missing for the defined midpoint category governance, which makes it nearly impossible to determine the relevance of this indicator for SLCA. Doubtless of course are the interconnections of governments and social effects (Evans, 1996), but however for SLCA it is recommended to include these effects into existing indicators, e.g. human rights, rather than to name it in a separate impact category. Therefore, within this study socio-economic repercussions and governance are not considered as own impact indicators.

As it can be taken from Table 3, Tier 3 is meant to complement the indicator selection for the three dimensions. Therefore, even indicators have been included, which are not necessarily in broad practical use. This comprises indicators, like ecotoxicity or land use for LCA; investment cost or taxes for LCC, and education or human rights for SLCA. The implementation of those indicators represents a great challenge, which should be preferably undertaken at a more advance level of LCSA. An even greater challenge can be seen in the interpretation of results at this level (comparable to the argumentation of Tier 2), as characterization models are lacking, different perspectives and stakeholder groups need to be considered and quantitative, semi-quantitative and qualitative indicators are included at the same time. Therefore, caution is needed and all indicator results must be displayed separately and transparently. Hence, also a previous weighting of results is not targeted by the authors, as no quantitative comparison is foreseen, but rather a verbal argumentative discussion on the results. Therefore, the concrete number of indicators is not especially relevant at this stage.

4. Discussion

The Tiered approach consists of a hierarchical indicator structure and guides one through LCSA orientated on the three criteria practicality, relevance and method robustness. Successively, additional indicators are implemented towards a comprehensive level of LCSA starting from the basic ‘sustainability footprint’. Targeting the enhancement of the practical implementation of LCSA, which is seen as one needed requirement to enhance further improvement of methods and science in this field, the entrance level was lowered by means of Tier 1 – the sustainability footprint. This simplification may be accompanied by lacking robustness of results and conclusions from Tier 1 to Tier 3, which can be named as one potential drawback of the Tiered approach. Contradictions in results may occur through the stepwise implementation of indicators. An option which has been identified as more sustainable within Tier 1 might turn out to be less sustainable after the complete set of indicators of Tier 2 or 3 have been applied. Thus, final conclusions based on results gathered within Tier 1 are not recommended. The same applies to carbon footprint results in comparison to full LCA, where trade-offs are likely to occur between climate change and other impacts. In addition, LCSA is seen as an iterative process (orientating on LCA) and therefore all indicators included are to be double-checked after each tier, regarding completeness and consistency.

As LCSA is still in its infancy, indicators for the economic and social dimension are often not mature. However, the Tiered approach promotes the idea of getting started instead of getting lost in perfectionism; similar has already been stated at the United Nations Conference (UNCED, 1992). Therefore, available indicators were considered and the related shortcomings were mentioned (see supplementary data). This study does however not target the further development of the characterization methods themselves, but initiates a reasonable bottom-up process by giving prioritization for different topics and indicators. Nevertheless, further research and case studies are needed to enable a verification of the chosen indicators. Furthermore, case studies are essential to revise the already made assumptions for Tier 1 regarding easy implementation and for Tier 2, which addresses the ‘best-practice’. However, the ranking for the three tiers was performed based on the defined criteria and according to best knowledge, even if transitions are often floating (see supplementary material). Consequently, additional indicators or midpoint impacts may and

[7] http://www.un.org/millenniumgoals/.

[8] http://www.hrw.org/de.

[9] Cultural heritage is e.g. addressed by *Cultural Heritage without Borders* (http://chwb.org/).

should be included, whenever new research cognitions are gained and justified.

Weighting is neither recommended nor foreseen within the Tiered approach, as at this stage only a verbal argumentative discussion of results seems reasonable. Normalization may be applied, but does not seem broadly applicable especially for LCC and SLCA, due to unclear impact and indicator definitions and missing reference quantities. More research is furthermore needed in order to claim, if and when the three dimensions are equally represented. This can be seen as one foundation to enable valuable recommendations on how to deal with the LCSA interpretation phase; foremost, as the three methods differ significantly in degree of maturity and thus an offsetting between the dimensions might lead to wrong assumptions. For the interpretation phase of LCSA, the Tiered approach does not present solutions, but it allows a transparent display of the results gathered for the single dimensions, as well as for the single indicators.

Although, the existing challenges of LCSA, which were also mentioned earlier by Klöpffer (2008) and Finkbeiner et al. (2010), have not been completely solved by means of the Tiered approach; it significantly enhances transparency within the current assessment practice and points out research needs. However, as a next step case studies need to be performed to test the approach for different fields and products. Adjustments on this basis are possible, as the Tiered approach is easily adaptable to new findings and flexible for the inclusion of additional indicators. In this context, e.g. the inclusion of a fourth tier seems useful to include endpoint impact indicators and to also display the complete impact pathway and the occurring inter-linkages within and between the sustainability dimensions.

5. Conclusions

The practical application of LCSA is still lacking due to large implementation efforts and methodological challenges. Moreover, especially SLCA and LCC seem to be stuck in a methodological vacuum. For the further development of LCSA the provision of a meaningful indicator selection appears important, particularly as method developments may depend on considered indicators. The corresponding indicator selection has been provided by means of the Tiered approach. Therefore, indicators for the three methods LCA, LCC and SLCA have been ranked according to the three criteria relevance, method robustness and practicality. The related research has been presented within the supplementary material. Accordingly, the Tiered approach may be beneficial in at least two ways for the field of LCSA. First, the included indicators have undergone a comprehensive review, which seems essential as a basis for further (methodological) developments within the LCSA framework. Secondly, the presented indicator hierarchy provides directions for data selection processes necessary to perform case studies. Furthermore, by means of the 'sustainability footprint' (Tier 1) practical implementation is facilitated, as the LCSA entrance barrier was lowered without neglecting one dimension of sustainability. LCSA may become more understandable and tangible, due to the given indicator structure. In addition, trade-offs between the three pillars will become more transparent, as all three methods have been addressed from the very beginning. Thus, the Tiered approach may enhance a more consistent way of dealing with LCSA by avoiding inconsistent approaches, which randomly include indicators into the LCA framework in order to also express social and economic performance. In addition, the Tiered approach may enhance the understanding of products and processes from a sustainability point of view, as hotspots and impacts can be identified more easily.

Acknowledgement

We acknowledge that this research is funded by the German Research Foundation DFG (SFB 1026/1 2012), Collaborative Research Center CRC1026 (Sonderforschungsbereich SFB1026).

List of acronyms

AoP	Area of protection
HIV/AIDS	Human immunodeficiency virus infection/Acquired Immune Deficiency Syndrome
ILCD	International Reference Life Cycle Data System
ILO	International Labour Organization
IPCC	Intergovernmental Panel on Climate Change
JRC	Joint Research Centre
LCA	life cycle assessment
LCC	life cycle costing
LCSA	life cycle sustainability assessment
OECD	Organisation for Economic Co-operation and Development
PROSA	Product Portfolio Analysis (German: Produktlinienanalyse)
SD	Sustainable Development
SELCA	social and environmental life cycle assessment
SHDB	Social Hotspot Database
SLCA	social life cycle assessment
SWOT	Strengths, Weaknesses, Opportunities, Threats
UN	United Nations
UNCED	United Nations Conference on Environment and Development
UNEP	United Nations Environment Programme
WHO	World Health Organization
WMO	World Meteorological Organization

Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jclepro.2015.04.053.

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Maximum Sustainable Yield

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Introduction

Although the term "over-fishing" was coined already in the mid-1850s (Cleghorn, 1854), the overexploitation of marine fisheries resources was only realized in the early 1900s, when the first study (Garstang, 1900) and articles on overfishing (Petersen, 1903; Kyle, 1905) were published. By that time, the need for simple and easy to understand guidance on catch limits emerged. The maximum catch that a population can support seemed to be an excellent reference point for fisheries management.

Maximum Sustainable Yield (MSY) is the most well-known acronym in fisheries science and, as a concept, has a history of around 100 years (Baranov, 1918). It was formulated in the 1930s when mathematical models were introduced in population ecology (Hjort et al., 1933) and bloomed in the 1950s with the development of surplus production models.

Today, MSY has been adopted by the vast majority of regional management bodies (Hilborn and Walters, 1992; Quinn and Deriso, 1999; Mace, 2001; Hart and Reynolds, 2002; EC, 2009; Pauly and Froese, 2014) and it is therefore widely used as a reference point in the assessment of exploited populations (stocks) around the world.

The MSY Concept

Definition of MSY

MSY (also called maximum surplus production, maximum equilibrium catch, maximum constant yield, maximum sustained yield, sustainable catch: Ricker, 1975; Hilborn and Walters, 1992; Quinn and Deriso, 1999; Mace, 2001) is the highest theoretical equilibrium yield that can be continuously taken from a stock under existing (average) environmental conditions (FAO, 2001). It is the highest catch that still allows the population to sustain itself indefinitely through somatic growth, spawning, and recruitment (Graham, 1943; FAO, 2001).

MSY was formally introduced by Milner Schaefer (Schaefer, 1954) who developed the model named after him based on the logistic curve of population growth (Fig. 1). Plotting the first derivative (= the slope) of that curve over the corresponding biomass (the collective weight of the individuals at a certain time) shows the increase in biomass (termed surplus production or yield) with time, in the form of a parabolic curve (Fig. 2). The interpretation of the parabola is easy: at the left end there is zero biomass and therefore zero yield. At the opposite end, where the population is at carrying capacity of the ecosystem for this stock, there is no surplus production by definition and thus again zero yield. In other words, initially the population grows exponentially, unrestricted by environmental conditions. But as population size approaches carrying capacity, growth slows down and eventually seizes. Because of the symmetric shape of the logistic curve, maximum surplus production or yield is reached at half of maximum population size in the Schaefer model (Fig. 2; see "Methods to Estimate MSY section"). Taking away this maximum surplus production by fishing prevents the population from growing any further, basically keeping it at half of maximum population size, producing maximum surplus forever; hence this is the point of MSY.

In this simple model, the rate of population increase r is a linear function of biomass, maximum at zero population size, and zero at carrying capacity (Hart and Reynolds, 2002; Quinn and Deriso, 1999).

Various explanations have been offered for the typical S-shape of population growth, such as improved somatic growth at low population size versus increased intraspecific competition at high densities (Hart and Reynolds, 2002). Carrying capacity (K) has

 https://doi.org/10.1016/B978-0-12-409548-9.10601-3

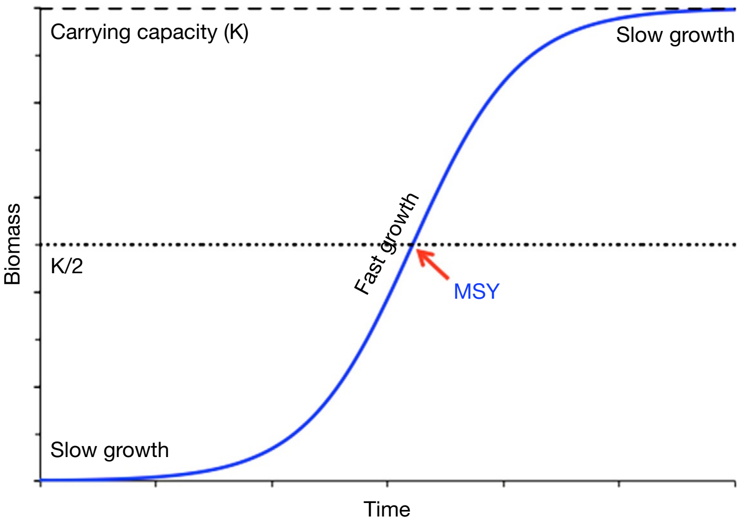

Fig. 1 The logistic (sigmoid) curve of population growth over time. The carrying capacity (K) and MSY (=K/2) are indicated along with phases of slow and fast population growth.

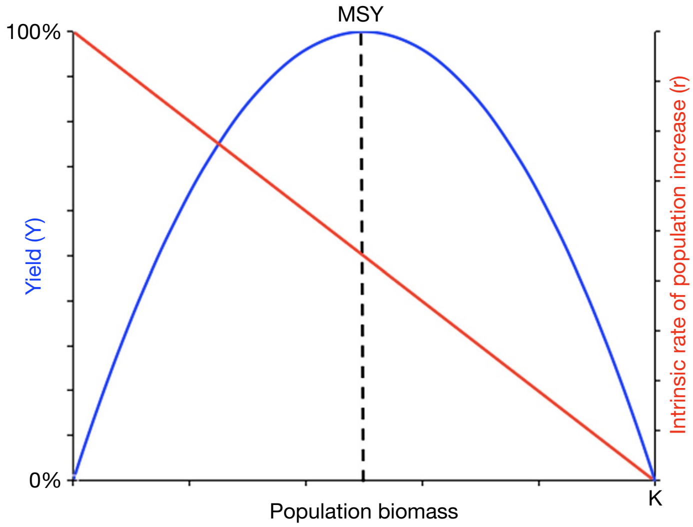

Fig. 2 The parabolic curve of surplus production or equilibrium yield (as % of MSY) as a function of population biomass (as % of carrying capacity, *K*). The second *Y*-axis shows the intrinsic rate of population increase r, which in the Schaefer model is maximum at zero biomass and declines linearly to zero at carrying capacity. Note that MSY is produced at half of r_{max}.

been interpreted in Malthus' terms as being caused by limited food availability (Seidl and Tisdell, 1999). However, today most ecologists agree that the main driver of population growth is the interplay between reproductive success and mortality (Charnov, 1993; Sibly et al., 2012): once the number of new individuals equals the number of deaths population growth seizes. At low population sizes, new individuals exceed the number of deaths and population growth is exponential. But while the number of deaths remains proportional to population size, the production of new individuals slows and reaches a more or less constant value once the population has grown beyond about a quarter of carrying capacity. As a result, the exponential growth slows to a linear growth at about half of carrying capacity and declines thereafter, approaching carrying capacity in an asymptotic curve (Fig. 3). Density effects causing death by starvation are thought to apply mostly to early life stages (Houde, 1987; Bailey and Houde, 1989; Hüssy et al., 1997) and cause a limit to reproductive success, as indicated by the green curve shown in Fig. 3.

Today, the MSY definition most widely used is the one proposed by Ricker (1975). According to "the green book" of Ricker, MSY is defined as the largest average catch or yield that can continuously be taken from a stock under existing environmental conditions but for species with fluctuating recruitment the maximum catch may be obtained by taking fewer fish in some years than in others (Ricker, 1975).

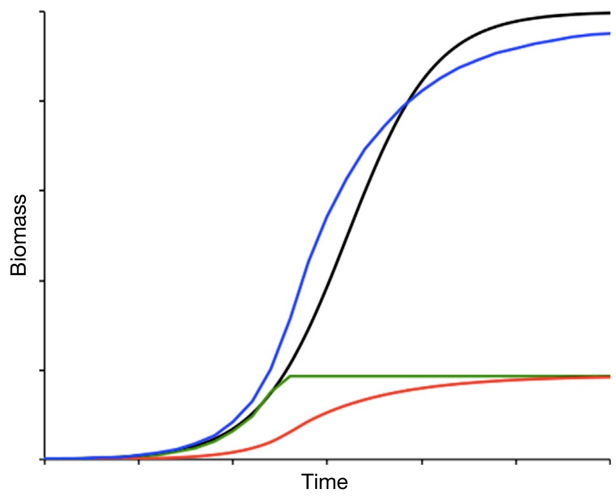

Fig. 3 The theoretical logistic curve of population growth over time (*black line*) compared with a hypothetical curve (*blue line*) resulting solely from the number of deaths (mortality: *red line*) and the number of replacements through recruitment (reproductive success: *green line*), which is more or less constant above about a quarter of carrying capacity.

Related Biological Reference Points

Current fisheries management is based on fishing mortality and biomass reference points that correspond to MSY, although MSY itself is rarely used as a reference point. Two related reference points are applied: one is the fishing mortality or fishing pressure (F_{MSY}) that, if applied over a time span similar to generation time, will eventually result in a catch equal to MSY (Fig. 4) where F describes the part of the total mortality rate that is caused by fishing. For example, $F = 0.6$ means that about 60% of the fish that are there on average over the year will be killed by fishing. The other related reference point is the biomass at MSY, B_{MSY}, which is the smallest stock size that can support catches equal to MSY, and which is the biomass corresponding to the peak in Fig. 2.

In age-structured assessment models, the fishing mortality that results in the maximum yield per recruit (F_{MAX}) is close to F_{MSY} if the yield per recruit versus F curve has a well-defined peak. However, if that peak is less well defined, as in Fig. 4, then F_{MAX} may be substantially larger than F_{MSY} (Longhurst, 2006).

Methods to Estimate MSY

MSY, $F_{MSY,}$ and B_{MSY} can be estimated from surplus production models, which require catch and effort or an index of biomass or relative abundance (e.g., catch per unit of effort) as input. Alternatively, these or similar reference points can be obtained from age-structured models, which are, however, more data demanding.

Surplus Production Models

Surplus production models are used to assess stock status and exploitation in data-limited areas where reliable information on age and length structure and natural mortality are not available (Beverton and Holt, 1957; Punt, 2003). They are applied not only to stocks with available commercial catch data and some index of exploitable biomass, such as catch per unit of effort (CPUE) derived from scientific surveys, but also to migratory stocks and crustaceans that are difficult to age (Polacheck et al., 1993). They assume that sustainable catch is a simple function of population biomass, regardless of the size and age composition of that biomass (Holt, 2014).

The most widely used surplus production model is the one developed by Schaefer (1954):

$$B_{t+1} = B_t + r_{max}B_t\left(1 - \frac{B_t}{K}\right) - C_t$$

where B_t is the biomass of the stock at time t and $t + 1$, r_{max} is the maximum intrinsic rate of population increase, K is a parameter which corresponds to the unfished equilibrium stock size or carrying capacity, and C is the catch per unit of time (usually a year).

Surplus production or yield (Y) is calculated as:

$$Y = r_{max}B_t\left(1 - \frac{B_t}{K}\right)$$

MSY is calculated as:

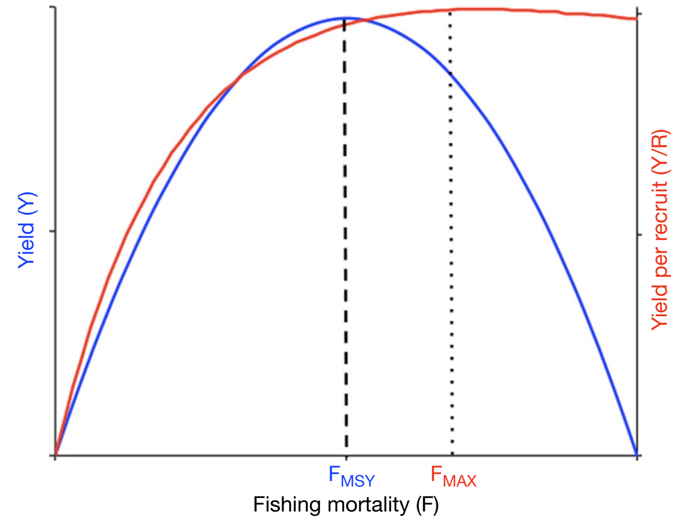

Fig. 4 Difference between the position of F_{MSY}, the fishing mortality expected to yield MSY in a surplus production model (*blue line*) and those of F_{MAX}, the mortality from yield-per-recruit curves (*red line*).

$$MSY = \frac{r_{max}}{2} \times \frac{K}{2} = \frac{r_{max}K}{4}$$

where $r_{\max}$ is the maximum intrinsic rate of population increase, B_t is the population biomass at time t, and K is the carrying capacity of the ecosystem for this population (Schaefer, 1954).

Another surplus production model was developed (Fox, 1970) that assumes a logarithmic relation between biomass and catch:

$$B_{t+1} = B_t + r_{max}B_t\left(1 - \frac{\log(B_t)}{\log(K)}\right) - C_t$$

where variables and parameters are as defined above.

In the Fox model surplus production or yield is calculated as:

$$Y = r_{max}B_t\left(1 - \frac{\log(B_t)}{\log(K)}\right)$$

MSY is calculated as:

$$MSY = \frac{r_{max}K}{e}$$

In the Schaefer model, maximum yield (MSY) is obtained at 50% of carrying capacity and in the Fox model at 37% of carrying capacity. Pella and Tomlinson (Pella and Tomlinson, 1969) proposed a model with a third parameter p that determines the shape of the yield curve and allows maximum production to occur at any biomass.

The Pella-Tomlinson model is:

$$B_{t+1} = B_t + \frac{r_{max}}{p}B_t\left(1 - \frac{B_t}{K}\right)^p - C_t$$

where variables and parameters are as defined above and p is a shape parameter that results in the Schaefer curve if $p = 1$ and approximates the Fox curve if p approaches 0.

Surplus production or yield is calculated as:

$$Y = \frac{r}{p}B_t\left(1 - \left(\frac{B_t}{K}\right)^p\right.$$

MSY is calculated as:

$$MSY = r_{max}K\left(\frac{1}{1+p}\right)^{\left(\frac{1}{p}+1\right)}$$

The Schaefer surplus production model is the one most commonly used in fisheries management because of its simplicity and applicability in data-poor stocks.

Age-Structured Models

In cases where age and length data are available, surplus production models have been replaced by age-structured models that also provide estimates of MSY and relevant reference points but these models are data demanding (Hilborn and Walters, 1992; Mace, 2001) and require population age and length, growth parameters, mortality and maturity, as well as selectivity of the main gears. Estimates of MSY, F_{MSY}, and B_{MSY} are typically obtained from stochastic simulations.

Age-structured models are widely used in assessing stocks and require estimates of mortality, maturity, catch, and abundance per age group, but these models are not suitable when only catch and biomass data are available.

Economic Considerations

Only 150 years ago, the advisor on fisheries to the British Government (Huxley, 1884) declared that humans were unable to overexploit marine fish stocks. The subsequent advent of steam trawlers and the collapse of North Sea herring (Dickey-Collas et al., 2010) proved him wrong and for over 75 years it was well understood that fisheries need to be regulated to sustain fish stocks and profitable fisheries (Graham, 1943). This can be easily demonstrated by adding cost of fishing (which increases about linear with effort) and profits (the difference between the value of the catch and the cost of fishing) to the parabola graph of the relation between yield and effort (Fig. 5). In most fisheries the cost of fishing at the MSY level is less than the value of the maximum sustainable catch and maximum profit or maximum economic yield (MEY) is actually obtained with even less fishing effort, simply because the linear decline in cost is steeper than the corresponding decline in catch near the peak of the parabolic curve (Fig. 5). Unfortunately, effort in most fisheries in the world is far above the MSY level resulting in low catches and economic loss (Costello et al., 2012; Froese et al., 2017). This is possible because governments give handouts (= subsidies) to the fishers, which lower the cost of otherwise economically unsustainable overfishing.

MEY is the antidote to the illusion of most fishers (and some politicians) that higher fishing effort results in higher profits. In reality, profits decline once effort exceeds the MEY level and catches decline once effort exceeds the MSY level (Fig. 5).

History and Legal Status of MSY

MSY is based on the classical ecological concept of logistic population growth that was developed in the 1830s (Verhulst, 1838), continuing the earlier work of Robert Malthus on demographics (Malthus, 1798). The first application of the logistic model on

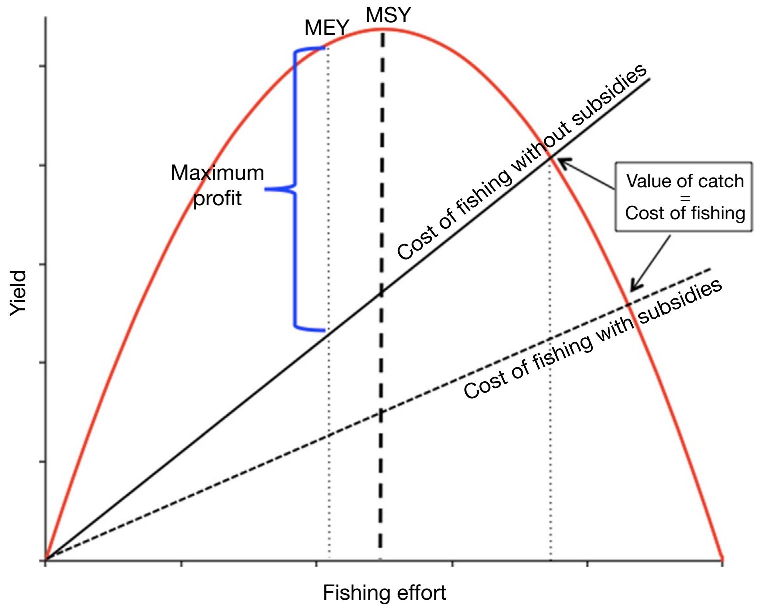

Fig. 5 Yield (*red line*) as a function of fishing effort, with cost of fishing with (*dashed black line*) and without subsidies (*continuous black line*) assumed to increase about linearly with effort. Profit is the difference between the value of the yield and the cost of fishing, with a maximum economic yield (MEY, *dotted vertical line*) obtained from effort and catches below the MSY level (*dashed vertical line*). If costs of fishing are lowered by subsidies, fishing can continue beyond the break-even point, where the value of the catch equals the cost of fishing (second *dotted vertical line*).

marine species was by Johan Hjort and his colleagues in the 1930s, who studied the blue whale fishery, based on mortality and reproduction data (Hjort et al., 1933). They developed the notion of optimal catch, which occurred at intermediate exploitation levels based on their observations on fin whales in Iceland, cod and herring in Norway, and plaice in the southern North Sea (Holt, 2014). Hjort et al. (1933) showed that the greatest rate of population growth increase occurs when the population size is about half its ultimate size and that there was a maximum catch that could be sustained, later termed MSY (Hart and Reynolds, 2002).

Shortly after Hjort's work, Michael Graham further developed the logistic population growth equation and applied it to fisheries data (Graham, 1935, 1943). He identified slow and fast population growth phases, with fast growth, low density and younger fish at low population sizes and slow growth, high density and many old fish at large populations near carrying capacity (Graham, 1935). Based on his observations from several species, he argued that "*a lower fishing rate would give as great a yield when the stock became stabilized at that rate*" (Graham, 1935). Later, Graham concluded that "After a certain point the total yield of a fishery does not increase any more, whatever the fishermen do" and clearly linked exploitation to economics when he wrote that "the benefit of efficient exploitation lies more in economy of effort than in increase of the yield" (Graham, 1943).

Schaefer (1954) developed the eponymous Schaefer model using the logistic growth curve on Californian sardine. He replaced population numbers with biomass and defined surplus production as yield. Thus, he formally introduced the concept of MSY, then termed maximum equilibrium catch (Schaefer, 1954). Schaefer preferred the expression maximum equilibrium catch to optimum catch "as being more descriptive of exactly what is meant" (Schaefer, 1954). Schaefer, who was working with tuna, had to ignore age composition because there was not, at the time, a way of determining the age of an individual tuna (Holt, 2014).

In fact, MSY was in use as a theoretical concept a few years before the publication of Schaefer's surplus production model, when it was adopted as the scientific foundation of the US High Seas Policy, in 1949 (Chapman, 1949; Finley, 2011). MSY adoption was largely based on Graham's theoretical analysis (Graham, 1943; see the section "History and Legal Status of MSY") and his conclusion that less fishing can provide in some cases more fish. It was later that MSY was quantified with the Schaefer's surplus production model, and then, in 1955, adopted as the goal of international fisheries policy at the Rome Conference on fisheries problems (Smith, 1994).

After the late 1950s, MSY has been adopted as the primary management goal by several international organizations (IWC, IATTC, ICCAT, ICNAF) and countries (Mace, 2001; Froese et al., 2011). The United Nations Convention on the Law of the Sea (UNCLOS, 1982) made the MSY approach mandatory for fisheries in the exclusive economic zones (EEZs) of its signatories, which were obliged to include the MSY concept into national or regional fisheries legislation (Mace, 2001). All 39 then existing regional fisheries organizations (RFMOs) agreed to manage their mandated stocks such that they were capable of producing MSY (Longhurst, 2006). The follow-up conference on the United Nations Fish Stocks Agreement (UN, 1995) clarified in its Appendix II that during a phase of reducing excessive fishing effort, the one associated with MSY could be used as a target, but that once that target had been reached, MSY had to be treated as a limit, that is, fishing effort should be less than the one resulting in MSY.

For example, in the MSA (2006) the goal of fisheries management is defined as "optimal yield," which is "prescribed on the basis of the MSY from the fishery, as reduced by any relevant economic, social, or ecological factor" (Froese et al., 2011). In addition, fisheries management based on MSY has been formally implemented in New Zealand (MFNZ, 2008), Australia (DAFF, 2007), and Europe (EC, 2013). In most of these areas MSY-based policies have been quite successful in rebuilding stock biomass (Hilborn, 2007a; Mesnil, 2012).

Critique of MSY

The implementation of MSY as a catch that can be taken continuously independent of recruitment, stock size, stock structure, and environmental conditions has been questioned and criticized early on (e.g., Beverton and Holt, 1957; Larkin, 1977; Sissenwine, 1978). Its assumptions, uncertainties, limitations, and misapplications have been repeatedly pointed out (Hilborn and Walters, 1992; Caddy and Mahon, 1998; Punt and Smith, 2001; Hilborn, 2007b; Kesteven, 1997; Holt, 2009). For example, MSY cannot be determined for a stock unless this stock is overexploited, that is, the top of the parabola (=MSY) needs to be well surpassed for it to be determined. Therefore, MSY and optimum fishing effort cannot be predicted in early stages of developing fisheries and stock assessments should focus on detecting it as rapidly as possible (Hilborn and Walters, 1992). Once MSY is detected, fishing effort should be reduced by up to 30% in order to achieve sustainability (Hilborn and Walters, 1992). Also, the assumption of average recruitment and average environmental conditions may lead to wrong advice in highly fluctuating stocks (Hilborn and Walters, 1992). The dependence of MSY on size at first capture and age structure in the stock is ignored (Longhurst, 2006; Holt, 2009; Anderson et al., 2008). MSY is achieved by setting limits on fishing mortality but, as different fishing gears select and target different composition of species and some species are not targeted at all, MSY is rarely attained simultaneously for all species within an area (Maunder, 2002). The social aspects mentioned in UNCLOS (1982) have often been misunderstood as allowing for temporary overfishing to secure employment. The recovery potential of depleted stocks is overestimated by the simple parabola (Quinn and Deriso, 1999; Hutchings and Reynolds, 2004).

It is argued that surplus production models are too simple to fully describe the dynamics of populations subject to variability in recruitment, interactions with other species, catchability, selectivity, environmental conditions, and changing climate (Pella and Tomlinson, 1969) and they require a good contrast between fishing effort and stock abundance (Hilborn and Walters, 1992).

Improving MSY

The epitaph for MSY of Larkin (1977) was rather premature (Barber, 1988) as it was referring to the early, simplistic application of MSY that was considered a viable fishing target with constant catch removal. MSY has been conceptually transformed through time and improved (Kesteven, 1997; Mace, 2001) to become a limit that should be avoided (*target reference point* refers to a desirable state at which management should aim while *limit reference point* refers to an undesirable state which management should avoid: Caddy and Mahon, 1998), which brings the MSY concept in line with contemporary scientific views (Mace, 2001; Mesnil, 2012). Concerning the social issues, there is no conceivable scenario where overfishing is good for society because it results in subsequent lower catches and food supply, and lower future profits and fewer jobs in the sector.

The wide-spread critique that MSY ignores environmental conditions and species interactions is actually overstated (Froese et al., 2017), because the key parameter r_{max}, the maximum intrinsic rate of population growth, summarizes in a single value the interplay of natural mortality (caused mostly by predation), somatic growth (driven by food availability), and recruitment (strongly determined by environmental conditions). In other words, environmental and climatic effects are summarized in their impact on the survival of adults, that is, natural mortality (M), the availability and nutritional value of food, and the effort associated with acquiring it are summarized in somatic growth (k), and the interannual variability in environmental conditions that determine the survival of eggs and larvae are summarized in recruitment (i.e., the number of individuals surviving to join the exploited population) (Pauly and Froese, 2014). In other words, varying food availability, interspecific relationships, environmental/climate changes, and selectivity of the fishing gear are all incorporated in r_{max}. Increasing size at first capture will increase MSY, overfishing of prey species will decrease MSY.

Because of species interactions such as competition for resources and predator–prey relationships it is not possible for all populations to deliver MSY at the same time (Walters et al., 2005). But achieving, for example, 90% of MSY for all commercial fish and shellfish will already result in a substantial overall reduction of anthropogenic mortality for most target and nontarget species and will restore their biomasses to levels that should allow them to fulfill their roles as prey and predators in the ecosystem (Mace, 2001).

Forage fish (anchovies, herrings, sardines, and sand eels) are the crucial link between lower and upper trophic levels in the food web because they transport energy from millimeter-sized phytoplankton and zooplankton to the larger fish eaters of the food web (Baxter, 1997; Pikitch et al., 2012). For that reason they must be fished less and should be used for human consumption rather than for animal feed (Froese et al., 2016a).

Conclusion

It is now well established that fisheries management failed to preserve fish populations and some scientists have blamed it on the MSY concept (e.g., Mesnil, 2012). But is it a matter of science or a matter of administration and policy if stocks are in bad shape? So far, MSY has not been proven wrong as a concept but its estimation was not always correct and the administrative measures taken for its adoption were often inadequate or inappropriate (Kesteven, 1997). After its reform and continuous update, MSY remains a useful concept and a realistic approach to fisheries management and administration (Kesteven, 1997) and according to an anecdotal quote attributed to John Gulland "MSY is the most important concept in fisheries management" (Mangel et al., 2002). On top of that MSY carries a simple message that appears sensible to politicians and stimulates support by the public (Mesnil, 2012) and for that reason it is still widely used in assessing stock status and exploitation. It can be easily improved by considering size structure and setting catch length (L_C) close to optimum length (L_{OPT}) (Froese et al., 2016b). If $F < F_{MSY}$ and L_C is close to L_{OPT}, "pretty good" catches below but close to MSY are possible, with minimized impact on stock and environment. Pretty good yield (PGY) is a term introduced by Alec MacCall (National Marine Fisheries Service, Santa Cruz, CA, United States, retired) in 2000, proposing catches of about 80% of MSY as a meaningful and realistic target.

Acknowledgment

The authors would like to thank Daniel Pauly, Kostas Stergiou, and Henning Winker for their helpful suggestions and comments.

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CHAPTER

3

Life cycle thinking tools: Life cycle assessment, life cycle costing and social life cycle assessment

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3.1 Life cycle assessment methodology

Life Cycle Assessment (LCA) methodology was born in order to face the need for methods for understanding and addressing environmental protection and the impacts of products. In other words, it was born to provide information to show the effects of an activity on the environment and to identify opportunities for making changes to reduce the environmental impacts (Perriman, 1993). Currently, the LCA methodology is standardized by two international standards, namely ISO 14040:2006 and ISO 14044:2006.

According to a well know definition given by SETAC, LCA is a methodology to evaluate the environmental burdens associated with a product, process, or activity. It identifies and quantifies energy and materials used and waste released to the environment; it assesses the impact of energy, materials, and releases to the environment; it identifies and evaluates opportunities for environmental improvements. LCA embraces the entire life cycle of a product, process, or activity, encompassing extraction and processing of raw materials; manufacturing, transportation, and distribution; use, reuse, maintenance; recycling, and final disposal (SETAC, 1993). Thus, it aims at assessing the environmental burdens through the identification and quantification of energy and materials consumed, waste produced, and possible environmental improvements at various points in the life cycle of products, processes, and activities.

Life Cycle Sustainability Assessment for Decision-Making
https://doi.org/10.1016/B978-0-12-818355-7.00003-8

The currently accepted definition of LCA is "compilation and evaluation of inputs, outputs, and potential environmental impacts of a product system throughout its life cycle," which typically occurs in four steps (ISO, 2006a,b), as shown in Fig. 3.1.

The first phase is the description of the goal and scope, which includes defining the objectives of the study and setting the system boundaries. The second phase, called inventory analysis, compiles inputs and outputs for each process in the life cycle and sums them across the whole system. Typically, several hundreds of emissions and resources are quantified. In the third phase, known as life-cycle impact assessment (LCIA), emissions and resources are grouped according to their impact categories and converted to common impact units to make them comparable. The final phase is the interpretation of the inventory and impact assessment results in order to answer the objectives of the study (Hellweg and Milà i Canals, 2014). A scheme representing the application of the LCA methodology is shown in Fig. 3.2.

Thanks to its characteristics, LCA is also used to inform decision-makers in industry, government, or nongovernment organizations; to select indicators of environmental performance; and to implement eco-labeling and make environmental claims. As a decision support tool, LCA is generally applied to a product, but also to a system or service (Tillman and Baumann, 2004). For instance, Liamsanguan and Gheewala (2008) used LCA as a decision support tool for environmental assessment of municipal solid waste management systems. Ramasamy et al. (2015) used LCA as a tool to support decision making in the biopharmaceutical industry, revealing considerations and challenges; whereas Means and Guggemons (2015) developed a framework for environmental decision-making based on LCA for commercial buildings.

Dong et al. (2018) analyzed the need and obstacles for integrating LCA into decision analysis, whereas Zanghelini et al. (2018) studied how multicriteria decision analysis is aiding LCA in results interpretation. LCA is also used as a support for decision making in the public sector; for instance, Guérin-Schneider et al. (2018) focused on how better to include environmental assessment in public decision-making in the case of wastewater treatment, and Jouini et al. (2019) developed a framework for coupling a participatory approach with LCA for public decision-making in rural territory management.

A detailed literature review on sustainable evaluation for energy systems carried out by Campos-Guzmán et al. (2019) revealed that LCA and multicriteria decision-making techniques, when used in combination within the same methodological framework, can be an effective tool for sustainable evaluation. In particular, the combination of LCA and analytic hierarchic process is often used for its simplicity and robustness for sustainable evaluation in energy systems.

3.1.1 Goal and scope definition

The goal definition comprises the identification of the intended application, the reasons for carrying out the study, the stakeholders involved, and how the results are intended to be used; i.e., if they are intended to be used in comparative assertion or if they are intended to be disclosed to the general public. The scope instead defines the dimension and detail of the study to reach the goal. In the scope, the following items have to be defined (ISO, 2006a):

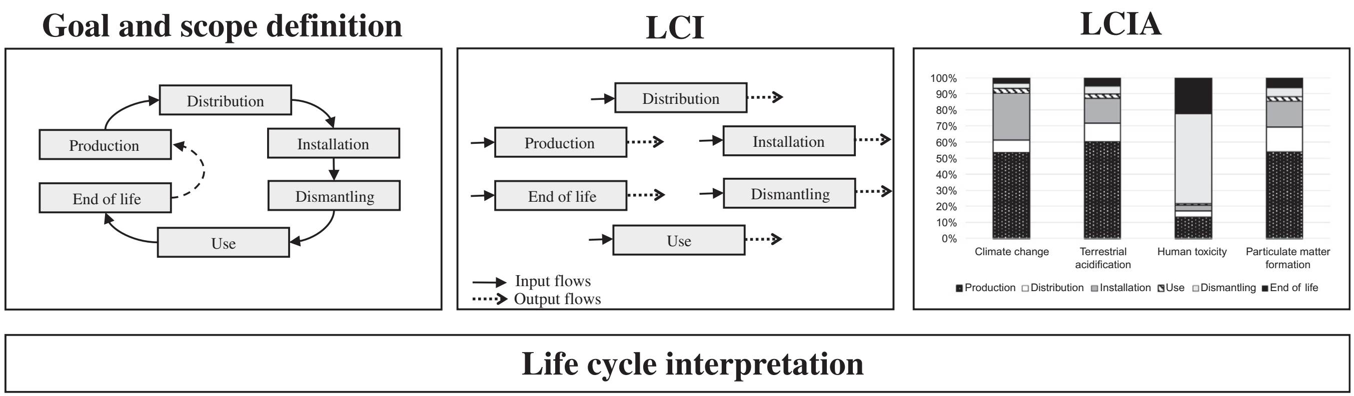

FIG. 3.1 Phases of the LCA methodology.

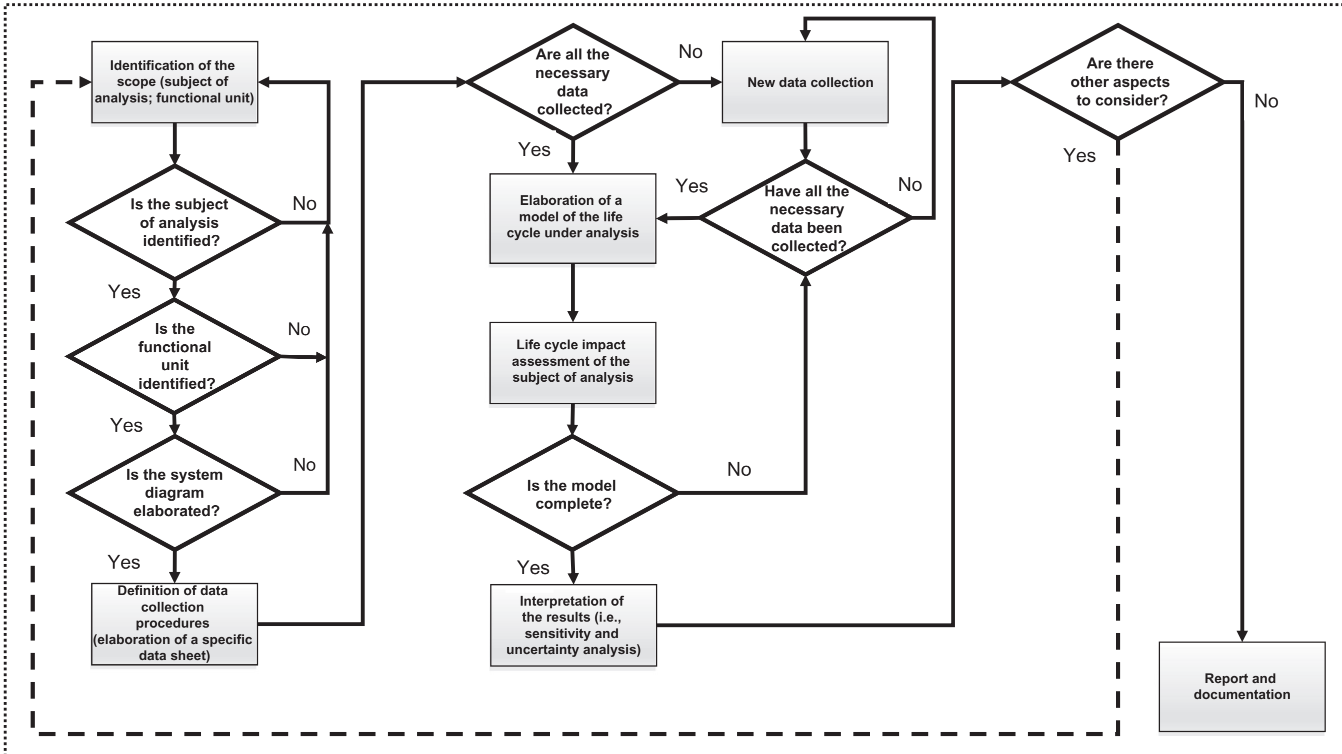

FIG. 3.2 Scheme representing the application of the LCA methodology.

– product system;
– functions of the product system;
– functional unit;
– system boundary;
– allocation procedures;
– impact category and methodologies of impact assessment;
– data requirements;
– assumptions;
– limitations;
– initial data quality requirements;
– type of critical review; and
– type and format of the report.

The main item is the functional unit, which allows quantifying of the identified functions of the system or product, is the reference unit for the calculation of the inputs and outputs, and ensures comparability in case of comparative studies. An LCA study has to be conducted by defining product system and the system boundaries, which are necessary to establish the functions to be considered. Ideally, inputs and outputs should be elementary flows. However, the choice of the elements of the system depends on the goal and scope of the study, the intended application, the audience, the assumptions made, data, cost and cut-off criteria (ISO, 2006a), namely the criteria to establish the threshold under which it is possible to exclude not significant environmental burdens.

3.1.2 Life cycle inventory (LCI)

This stage covers data collection and calculations to quantify the relevant inputs and outputs of the system. It is an iterative step and thus, further data requirements or limitations may be identified to meet the goal of the study during the conduction of the analysis. The main data required to conduct an LCA study are (ISO, 2006b):

– consumption of inputs;
– products, co-products and waste flows;
– emission to air, water, and soil; and
– other environmental aspects.

Input and output data have to be organized as usage of raw material, water usage, energy consumption, emission into water, air, and soil, and waste. In addition, the following items have to be indicated (ISO, 2006a):

– data sources;
– reference process
– reference technology
– geographical area;
– monitoring details;
– measuring methods; and
– specific units of measurement.

After data collection, a calculation procedure to validate the collected data has to be implemented; data have to be connected to the unit process and to the reference flow of the functional unit. These actions are necessary to generate the results of the inventory phase.

In this phase, a required item concerns allocation procedures. The main problem is which flows and environmental interventions must be allocated to the functional unit, and which should be allocated to other product systems. Within LCA studies, two different cases have to be distinguished for the application of allocation procedures (Toniolo et al., 2017a). The first case occurs when simultaneous products are manufactured and thus, different inputs and outputs shall be allocated to different products, whereas the second case occurs when subsequent products are realized in recycling or reuse systems. In general, almost all of the industrial processes produce more than one product or recycle a portion of the waste material (Frischknecht et al., 2005, 2007; Frischknecht, 2010).

However, even if in general allocation procedures represent a critical point (Ardente and Cellura, 2012), this distinction is not deeply investigated in ISO 14040 and ISO 14044. Anyway, it is possible to appeal to ISO TR 14049 where some examples are described and some considerations are added. Other considerations can be found in the ILCD (International reference Life Cycle Data system) handbook. If the market value of the waste or end-of-life product at its point of origin is above zero, in LCA perspective, it is a co-product and the multifunctionality has to be solved by allocation. However, the case of recycling is insofar different from the general case of multifunctionality, as the secondary good is not only a co-function of the system, but is itself recycled again and again (while each time at lower amounts and/or quality, considering losses of each loop) (EC-JRC, 2010).

3.1.3 Life cycle impact assessment

In this phase, the effects of the substances on the selected impact categories and the processes that generated them are analyzed (Toniolo et al., 2017b). Inventory data are associated with environmental impact categories and category indicators. The elements within this phase are (ISO, 2006b):

– Classification. Classification assesses which global/local impact the input/output is contributing to. There are input-relating categories and output-related categories. There are several categories that are commonly used, such as climate change, ozone layer depletion, eutrophication, acidification, particulate matter formation, and several impact categories under development, such as acoustic impact.
– Characterization. Impacts are quantified within given categories with the general Eq. (3.1) (Goedkoop et al., 2013):

$$EP(j)i = Q \times EQ(j)I \tag{3.1}$$

where $EP(j)i$ is the environmental impact of substance i with reference to the impact category j, Q is the quantity of substance I, and $EQ(j)i$ is a factor representing the substance i contribution to the impact j. Different substances contributing to an environmental impact are aggregated considering their substance-specific effect. Scientific models are used, therefore characterization could be considered objective. Fig. 3.3 shows an example of characterized results of an LCA study.

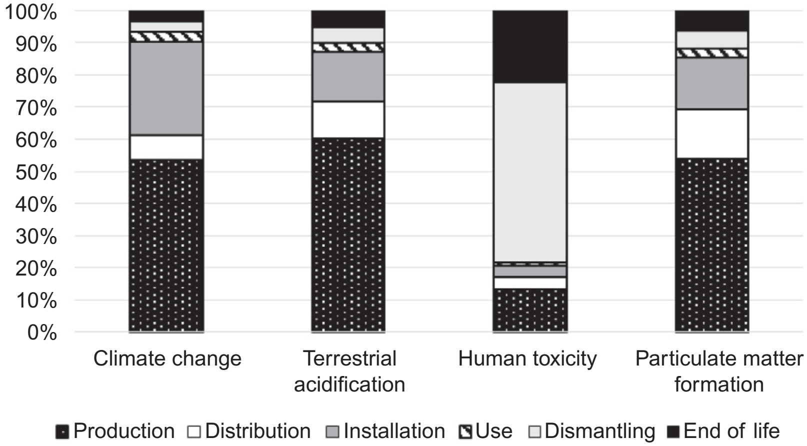

FIG. 3.3 Example of LCIA results.

- Normalization. The aim of normalization is to clarify the relative importance of the indicator results. Values are divided with reference to a standard value.
- Weighting. The categories results are assigned numerical factors in accordance with their importance, then multiplied by these factors and finally aggregated in a single impact score.

Classification and characterization are mandatory elements, whereas normalization and weighting are discretionary (ISO, 2006a).

3.1.4 Life cycle interpretation

In this phase, the results of the LCI and LCIA are considered together with reference to the objective of the study. The interpretation is comprised of several elements (ISO, 2006a,b):

- Identification of the significant issues based on the results of the LCI and LCIA phases. The objective of this step is to analyze the results from the LCI or LCIA phases in order to help determining the significant issues, in accordance with the goal and scope definition.
- An evaluation that considers completeness, sensitivity, and consistency checks. During this evaluation, the following techniques should be used: completeness check, sensitivity check, consistency check. The results of uncertainty analysis and data quality analysis should supplement these checks. The completeness check is performed to control that all the needed data and information are available and complete; the sensitivity check is performed to evaluate the reliability of the results; and the consistency check is conducted to determine whether assumptions, methods, and data are coherent with the goal and scope defined.
- Conclusions, limitations and recommendations.

3.2 Life cycle costing methodology

The use of life cycle costing (LCC) was reported for the first time in a tractor delivery contract in the 1930s in the United States (Ciroth et al., 2011); it was also used in the US Department of Defense in the mid-1960s for the acquisition of high-cost military equipment (Gluch and Baumann, 2004; Hoogmartens et al., 2014). Some attempts were made in the mid-1980s to adapt LCC to building investments and several research projects have been developed to adapt the LCC methodology for the construction industry and for sustainable public procurement, placing LCC in an environmental context (Gluch and Baumann, 2004). Therefore, we can say that LCC is not a new concept (Heijungs et al., 2013).

The LCC technique is often used to examine the preferable alternative of products and services from an economic point of view (Dragos and Neamtu, 2013), to ensure the ranking of different investment alternatives, and the adoption of the best solution, moving beyond the purchase price of a good or a service, and using a long-term approach for the decision-making process (Woodward, 1997). It has also become an important economic tool for decision-making, as it is used to evaluate the costs associated with an item in its whole life cycle, from its design through its production, transport to its end of life, and it is often applied in combination with LCA (Di Maria et al., 2018; Buyle et al., 2019).

For instance, Choi (2019) applied LCC and LCA in the case of maintenance and rehabilitation of highway pavement; whereas Xue et al. (2019) applied them for urban water system. Several combined applications exist for the building sector; i.e., Auer et al. (2017) conducted a case study on the performance of a modernized manufacturing system for glass containers. Schmidt and Crawford (2017) developed a framework for the integrated optimization of the life cycle greenhouse gas emissions and cost of building for buildings. Balasbaneh et al. (2018) analyzed the choice of different hybrid timber structures for low medium cost single-story residential buildings. Mah et al. (2018) studied the application of LCA and LCC for the management of concrete waste generated during the construction and demolition stages, and Hong et al. (2019) for building design.

In addition, several authors combined LCC with LCA and multicriteria decision analysis methods, among which Miah et al. (2017) proposed a novel hybridized framework combining integrated methods for LCA and LCC to provide decision-makers a comprehensive method to investigate environmental and economic aspects. They used a hybrid method combining the technique for order of preference by similarity to ideal solution (TOPSIS) and analytical hierarchy process (AHP). Harkouss et al. (2018) applied a multiobjective optimization methodology for net zero energy buildings using multicriteria decision making and LCC; whereas Invidiata et al. (2018) proposed a method that combines adaptive thermal comfort, climate change, LCA, LCC, and multicriteria decision making to identify the best design strategies for improving buildings.

Kouloumpis and Azapagic (2018) presented a new model, which integrates LCA, LCC, and Social LCA into a fuzzy inference framework; while Rocchi et al. (2018) conducted a sustainability evaluation of retrofitting solutions for rural buildings through LCA and multicriteria analysis.

The main difference between other traditional investment calculus methods and LCC is that LCC has an expanded life cycle perspective. The life cycle cost of an item is the sum of all costs expended from its conception and production, through its operation, to the end of its useful life (Woodward, 1997). LCC helps shifting from the best value for money to the best value across the asset life cycle (Perera et al., 2009), and includes a comparison between options or an estimation of future costs at portfolio, projects, or components over a defined period of analysis (ISO, 2011). It allows evaluation of the cost of acquisition, development, operation, management, repair, disposal, and decommissioning (Langdon, 2006; Reidy et al., 2015).

Therefore, LCC can be used both by private and public organizations to optimize the cost of acquiring, owning, and operating physical assets over their useful lives, trying to evaluating all the significant costs involved in the life cycle (Woodward, 1997). According to Woodward (1997), the costs of an item can be comprised of engineering and development costs, production and implementation costs, operating costs, and end of life costs. For instance, production and implementation costs comprise the initial capital costs, namely purchase costs, which include assessment of goods like land and buildings; they can be obtained through quotations from suppliers. There are also acquisition/finance costs, which include the cost effect of alternative sources of funds and regulations and installation/commissioning/training costs, which include the installation of machines and the training of the workers. An important concept is the life of the asset, which defines its life expectancy and decisive factors considering functional life, physical life, technological life, economic life, and social and legal life (Woodward, 1997). Associated with the concept of the life of an asset, there is the concept of the discount rate. The selection of the discount rate is a fundamental phase in LCC application. A high discount rate will tend to facilitate options with low capital cost, short life, and high recurring cost; whereas a low discount rate will have the opposite effect.

A way to define the discount rate in LCC studies was proposed by Islam et al. (2015). They calculated future costs, for instance for operation, maintenance, and demolition, using Eq. (3.2); then they discounted them using Eq. (3.3). Because of future risk, the discount rate exceeds the inflation rate.

$$FC = PC \cdot (1+f)n \tag{3.2}$$

where FC = future cost, PC = present cost, f = inflation rate, and n = number of years.

$$DPV = (1+d) \tag{3.3}$$

where DPV = discounted present value, FC = future cost, d = discount rate, and n = number of years.

In the scientific literature, three possible types of LCC emerge, namely conventional LCC, environmental LCC, and societal LCC (Hunkeler et al., 2008). The conventional LCC is the assessment of all the costs associated with the life cycle of a product. The focus of the evaluation is on real, internal costs and sometimes the costs of the end of life are not included. The environmental LCC is the evaluation of all the costs associated with the life cycle of a product covered by the actors in the product life cycle, for instance suppliers, manufacturers, users or consumers, and end of life actors. However, the environmental problems are simplified, since it assumes that everything can be expressed as a one-dimensional unit, such as monetary flows (Gluch and Baumann, 2004). The societal LCC includes all the costs that are associated with the entire life cycle of a product. These costs are covered by anyone in the society, today, or in the long-term future (Hunkeler et al., 2008).

Contrary to LCA methodology, which is standardized by two ISO standards, LCC is not structured by a specific international standard. The standard ISO 15686-5:2008 provides the instructions and the guidelines for the application of this methodology in the building sector, thus it cannot be applied to other contexts. However, some authors propose a methodology comprised of 10 steps to conduct an LCC study. All the 10 phases are required; they can be implemented in sequence, but also out of sequence, or sometimes simultaneously (Dhillon, 2010). The 10 steps are as follows (Dhillon, 2010):

1. Determine the purpose of the LCC analysis.
2. Define and scope the system/support system.
3. Select the appropriate estimating methodology/LCC model.
4. Gather data and make the appropriate inputs to the methodology/model.
5. Perform sanity checks of input and outputs.
6. Perform sensitivity analysis and risk assessment.
7. Formulate the results of the LCC analysis.
8. Document the LCC analysis.
9. Present the LCC analysis.
10. Update the LCC analysis/baseline.

The steps proposed by Greene and Shaw (1990) can be grouped in four phases, in line with LCA methodology, as reported in Fig. 3.4.

3.2.1 Goal and scope definition

The identification of the purpose for conducting an LCC study is the first necessary step. In some cases, the purpose may be obvious or predetermined, as in a source selection LCC analysis. Nevertheless, in other cases, when the purpose is not sufficiently clear, considerable efforts can be made before understanding the direction of the study. In this phase, the required issues to conduct the study are defined, including the criteria to be used for selection of alternatives. The goal of an LCC analysis may be a comparative analysis of a new system versus an existing system, or provisioning purposes (Greene and Shaw, 1990). The scope definition includes the system units to be included in the study, the definition of the subject of the study, the definition of assumptions, and the identification of limitations.

Usually, the system and subsystems are not completely defined until the final design, and the scope need to be revised. In the beginning of the study, the system definition and the scope may be vague. If the system under analysis is replacing or is similar to an existing system, it is important to include similarities and differences. This step is fundamental to ensuring a credible LCC analysis (Greene and Shaw, 1990). The selection of an appropriate LCC model depends on several factors, such as the type of system/support system/subsystem to be analyzed, the system units included in the life cycle and the type of analysis to be conducted, as defined in the first step.

The amount of data available to conduct an analysis is determined by the phase of development of the product or process under analysis. Only limited data may be available during the research and development phase, and so for instance parametric cost estimating models can be appropriate. If the product is under production, or a process is operative, there may be

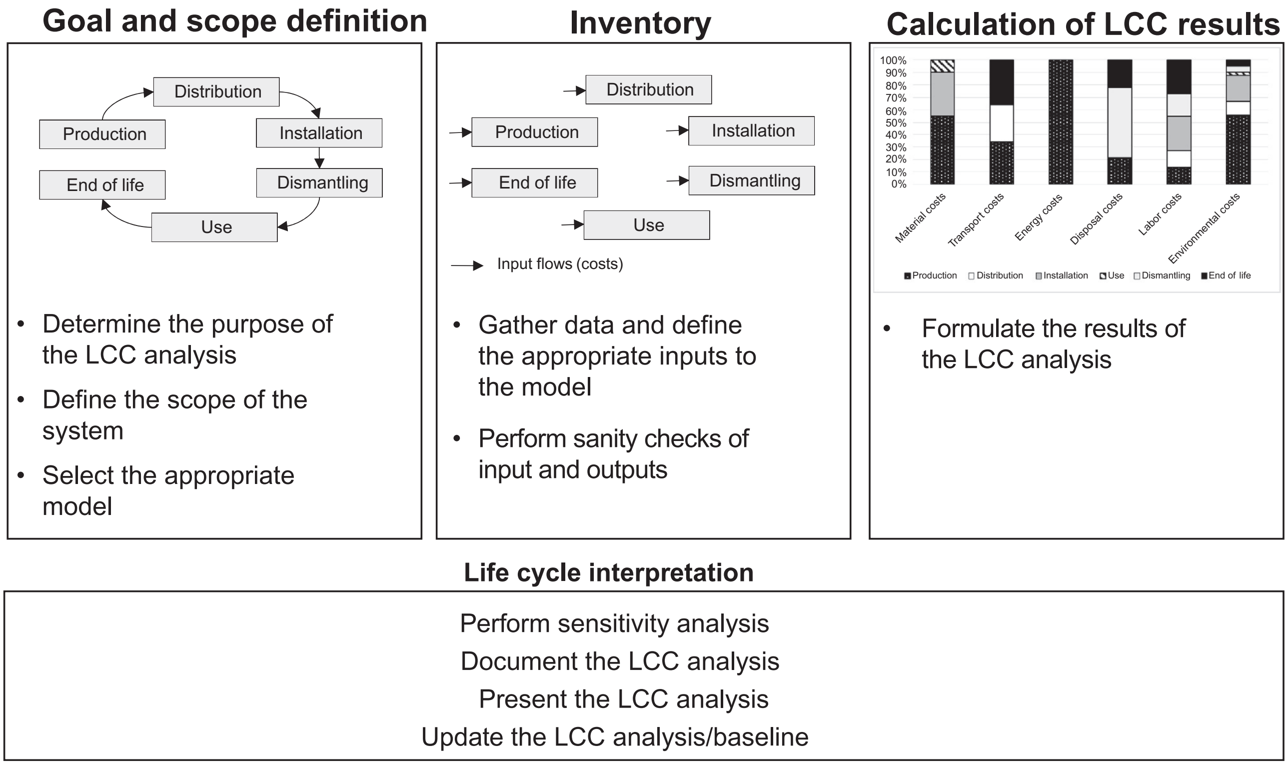

FIG. 3.4 The steps proposed by Greene and Shaw (1990) to perform an LCC study grouped in four phases.

enough information for an engineering bottoms-up estimation model. The model could refer to the number of operating hours a system accumulates. Different models are appropriate for each situation, for instance it is possible to use an operating hour driven model, or a periodic inspection, or a periodic exercise driven model. For a system or subsystem trade study, it can be appropriate to use a bottom-up rather than a top-down model. This means that a perfect LCC methodology/model that fits all applications does not exist. In any case, the selected model has to be documented properly, has to be verified and validated, and has to contain all the elements that need to be covered (Greene and Shaw, 1990).

3.2.2 Inventory

Data collection is a significant, time-consuming phase. Data can be collected from different sources, it is possible to collect data in the plant where the product is realized or the process occurs, directly. However, sometimes, it is necessary to make use of data from technical reports, from the scientific literature, or it can be necessary to do some estimations. The input and output data have to be checked in terms of consistency, accuracy, validity, and completeness to make sure that erroneous information is not present in the analysis or that required information has not been neglected. This step is important in order to avoid misinformation coming out of the analysis and to improve the credibility of the analysis.

3.2.3 Calculation of LCC results

After the collection of all the needed data, the implementation of the LCC model, and the making of the sensitivity or risk assessment, the results of the LCC study can be calculated. If there is the need to revise some methodological choices, it is possible to revise previous phases, such as the purpose of the study, and adjust the study. In this step, it is necessary to evaluate possible alternatives and identify the factors that significantly affect the LCC study. During this step, the results of LCC analysis can be inflated or discounted.

3.2.4 Interpretation

The input parameters with significant risk and high potential for impacting cost need to be varied over a reasonable range. It is possible to use the "best case," the "worst case," or something in between. LCC evaluations are estimations regarding the cost range, which can be expressed in a statistical way, or through a model with a limited number of parameters. The results of the LCC study have to be documented, along with the information to support the analysis.

3.3 Social life cycle assessment methodology

Social life cycle assessment (S-LCA) is a novel methodology to address the social impacts of products and services along their life cycle. It is based on LCA methodology, with some adaptations, and was developed in accordance with the ISO 14040 and 14044 standards (Ekener Petersen, 2015). It has been applied in different sectors, such as food, biofuels, materials, technology, and services (Vasta et al., 2015).

According to the definition given by UNEP/SETAC (2009), S-LCA is an assessment technique to evaluate the social and socio-economic aspects of products and their potential impacts along their life cycle from extraction and processing of raw materials to final disposal, passing through manufacturing, distribution, use, reuse, maintenance, and recycling. This technique tries to assess the social impacts of a product or service where social impacts are mainly understood as the impacts on human capital, human well-being, cultural heritage, and social behavior (Sala et al., 2015). These impacts can be associated with the behaviors of enterprises or with their processes and can be positive or negative. They are consequences of social interactions raised during an activity, such as production, consumption, or disposal (UNEP/SETAC, 2009). The basic idea is that social impacts could be embodied in products and related to supply chains (Sala et al., 2015). S-LCA can be a profitable tool to give answers to the following questions: what is the social value of products? How to define it, and to quantify it? (Russo Garrido et al., 2018).

S-LCA can be applied on its own or in combination with LCA, using generic and site-specific data (UNEP/SETAC, 2009). However, the level of methodological development, application, and harmonization of S-LCA is still at a preliminary stage (Sala et al., 2015). Contrary to other social assessment techniques, it takes into consideration the entire life cycle of a product or a service and helps in evaluating the social impacts that directly affect stakeholders. The stakeholders considered are clustered in five categories based on shared interests, namely workers/employees, local community, society, consumers, and value chain actors. Each category of stakeholders is associated with specific subcategories, for instance workers/employees are linked to the subcategories “freedom of association,” “child labor,” “fair salary,” “working hours,” “forced labor,” “discrimination,” “health and safety,” and “social benefits.” Consumers are linked to the subcategories “health and safety,” “feedback mechanism,” “consumer privacy,” “transparency,” and “end of life responsibility” (UNEP/SETAC, 2009).

In general, there are two methodological approaches to conduct S-LCA, called “performance reference point” methods and “impact pathways” methods. Performance reference point methods take into consideration living and working conditions of workers at different life cycle phases; whereas impact pathways methods evaluate the social impacts using characterization models with indicators similar to LCA (Sala et al., 2015). Different S-LCA methodologies have been proposed in several case studies and discussions are still open in the research community regarding the role of local stakeholders and the need of a common social theory as base to develop S-LCA (Ekener Petersen, 2015). It is still under debate whether qualitative or quantitative assessment methods are more suitable for S-LCA; indeed, a certain level of subjectivity cannot be avoided (Sala et al., 2015) and social issues are influenced by the subjectivity of researchers and the social context (Soltanpour et al., 2018). Despite this, S-LCA should be used to support decision making by different actors, identifying how to reduce the social hotspots along the supply chain (Sala et al., 2015), and can support the organizations within decision-making processes by optimizing the efforts and resources in order to achieve social sustainability (D’Eusanio et al., 2018). Currently, S-LCA is used as a business-oriented methodology, where the social assessment is based on the behavior of the organizations that are involved in the processes under study (Arzoumanidis et al., 2018).

Kolotzek et al. (2018) developed a model combining LCA and S-LCA for the assessment of raw material supply risks and used the analytic hierarchy process to weight the indicators. Santos et al. (2017) performed an S-LCA of school buildings for higher education, focusing on the criteria of health and comfort. They used analytic hierarchic process to obtain the weighting scheme to rate social performance. Chandrakumar et al. (2017) elaborated a multicriteria decision support system based on an S-LCA framework for evaluating three sanitation system designs. They applied the analytic hierarchy process to solve their proposed model. Halog and Manik (2011) proposed a framework adopting LCA, LCC, S-LCA, and stakeholders analysis supported by multicriteria decision techniques for the assessment of the development of biofuel supply chain networks.

Currently, new guidelines are under development for the application of S-LCA, they will consider and incorporate methodological advancements and recent practical experiences. They will also deal with harmonization of S-LCA methods, specification of application of S-LCA for organizations, and scale up of scientific debate (Benoit Norris et al., 2018). The following phases are usually conducted to develop an S-LCA according to the current guidelines (UNEP/SETAC, 2009).

3.3.1 Definition of goal and scope

The first phase of an S-LCA study is the definition of the goal and scope of the study. A clear statement of purpose, namely the goal of the study and the intended use, is needed. Based on the goal, a critical review may be planned. It is important to take into consideration that the ultimate objective is improving of social conditions and of the socio-economic performance of a product throughout its life cycle for all of its stakeholders (UNEP/SETAC, 2009). Successively, the scope has to be defined; the function of the product under study, its utility, and the functional unit, defined in time and space need to be determined. To define the functional unity, the following properties need to be considered: functionality, technical quality, additional services, aesthetics, image, costs related to purchase, use, and disposal (UNEP/SETAC, 2009). The definition of the functional unit is a key issue; indeed, in some cases, it is difficult to conceptualize it (Sala et al., 2015), and even if it is required, it does not seem to be a common practice to define it (Arzoumanidis et al., 2018). In addition, the following actions need to be conducted (UNEP/SETAC, 2009):

- Determine the unit processes to be included in the assessment, namely the system boundaries.
- Organize data collection; identify which data will be collected, for instance generic or specific data.
- Specify impact categories and subcategories.
- Define the stakeholders involved and the type of critical review, if needed.
- Define the types of impact to be evaluated and the related indicators and methods.
- Define allocation procedures.
- Plan the interpretation and identify assumptions, limitations, analyze data quality.

3.3.2 Social life cycle inventory analysis

The life cycle inventory phase can be conducted performing the following actions: collecting data on unit processes and redefining the selected system boundaries if needed. Data to be collected may be primary or secondary data and data for characterization. Primary data sources can be audits of enterprise documentation and documentation of authorities, making use of participative methodologies, interviews, focus groups, questionnaires, and surveys (UNEP/SETAC, 2009; Arcese et al., 2013; Trevisani Juchen et al., 2018). Secondary data sources can be scientific literature, web search, and databases. Collected data and functional unit have to be related and aggregated when applicable (UNEP/SETAC, 2009). Collected data should meet a list of quality criteria, such as validity—data have to provide information on what is intended to be measured; relevance; completeness—data have to cover the needs of the study; and accessibility—data collection has to be well documented. Then, uncertainty analyses should be performed and the measurement methods to generate the data have to be analyzed in order to define if they are appropriate (UNEP/SETAC, 2009).

3.3.3 Social life cycle impact assessment

This is the third phase of an S-LCA. Its purpose is to aggregate inventory data within categories and subcategories and to make use of additional information to help in understanding the significance of the collected information (UNEP/SETAC, 2009). This phase can be conducted through some actions: selection of the impact categories, subcategories, and characterization models, classification, namely associating inventory data with categories and subcategories, and characterization, namely calculating the impacts for the subcategories indicators (UNEP/SETAC, 2009). Unlike in LCA, where impacts are mostly negative, social impacts can also be positive (Sala et al., 2015). Indicators for S-LCA can be quantitative or qualitative depending on the goal of the study (UNEP/SETAC, 2009). Contrary to LCA, where impacts are calculated through a multiplication between the inventory data and a characterization factor recognized by international scientific community, S-LCA can express the impacts through a scoring system, providing as estimation of the impact (UNEP/SETAC, 2009).

3.3.4 Social life cycle interpretation

During this phase, the significant issues are identified and consideration about completeness and consistency of the study are drawn. Finally, the level of engagement with stakeholders is evaluated; conclusions and recommendations are reported (UNEP/SETAC, 2009).

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Sciencexpress Research Articles

Planetary boundaries: Guiding human development on a changing planet

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The planetary boundaries framework defines a safe operating space for humanity based on the intrinsic biophysical processes that regulate the stability of the Earth System. Here, we revise and update the planetary boundaries framework, with a focus on the underpinning biophysical science, based on targeted input from expert research communities and on more general scientific advances over the past 5 years. Several of the boundaries now have a two-tier approach, reflecting the importance of cross-scale interactions and the regional-level heterogeneity of the processes that underpin the boundaries. Two core boundaries—climate change and biosphere integrity—have been identified, each of which has the potential on its own to drive the Earth System into a new state should they be substantially and persistently transgressed.

The planetary boundaries (PB) approach (*1*, *2*) aims to define a safe operating space for human societies to develop and thrive, based on our evolving understanding of the functioning and resilience of the Earth System. Since its introduction, the framework has been subject to scientific scrutiny [e.g., (*3*–*7*)] and has attracted considerable interest and discussions within the policy, governance, and business sectors as an approach to inform efforts towards global sustainability (*8*–*10*).

In this analysis we further develop the basic PB framework by (i) introducing a two-tier approach for several of the boundaries to account for regional-level heterogeneity; (ii) updating the quantification of most of the PBs; (iii) identifying two core boundaries; and (iv) proposing a regional-level quantitative boundary for one of the two that were not quantified earlier (*1*).

The basic framework: Defining a safe operating space

Throughout history, humanity has faced environmental constraints at local and regional levels, with some societies dealing with these challenges more effectively than others (*11*, *12*). More recently, early industrial societies often used local waterways and airsheds as dumping grounds for their waste and effluent from industrial processes. This eroded local and regional environmental quality and stability, threatening to undermine the progress made through industrialization by damaging human health and degrading ecosystems. Eventually this led to the introduction of local or regional boundaries or constraints on what could be emitted to and extracted from the environment (e.g., chemicals that pollute airsheds or waterways), and on how much the environment could be changed by direct human modification (land-use/cover change in natural ecosystems) (*13*). The regulation of some human impacts on the environment, for example the introduction of chemical contaminants, is often framed in the context of 'safe limits' (*14*).

These issues remain, but in addition we now face constraints at the planetary level where the magnitude of the challenge is vastly different. The human enterprise has grown so dramatically since the mid-20th century (*15*) that the relatively stable, 11,700-year long Holocene epoch, the only state of the planet that we know for certain can support contemporary human societies, is now being destabilized (figs. S1 and S2) (*16*–*18*). In fact, a new geological epoch, the Anthropocene, has been proposed (*19*).

The precautionary principle suggests that human societies would be unwise to drive the Earth System substantially away from a Holocene-like condition. A continuing trajectory away from the Holocene could lead, with an uncomfortably high probability, to a very different state of the Earth System, one that is likely to be much less hospitable to the development of human societies (*17*, *18*, *20*). The PB framework aims to help guide human societies away from such a trajectory by defining a "safe operating space" in which we can continue to develop and thrive. It does this by proposing boundaries for anthropogenic perturbation of critical Earth System processes. Respecting these boundaries would greatly reduce the risk that anthropogenic activities could inadvertently drive the Earth System to a much less hospitable state.

Nine processes, each of which is clearly being modified by human actions, were originally suggested to form the basis of the PB framework (*1*). While these processes are fundamental to Earth System functioning, there are many other ways that Earth System functioning could be described, including potentially valuable metrics for quantifying the human imprint on it. These alternative approaches [e.g., (*4*)] often represent ways to explore and quantify interactions among the boundaries. They can provide a valuable complement to the original approach (*1*), and further enrich the broader PB concept as it continues to evolve.

The planetary boundary framework: Thresholds, feedbacks, resilience, uncertainties

A planetary boundary as originally defined (*1*) is not equivalent to a global threshold or tipping point. As Fig. 1 shows, even when a global- or continental/ocean basin-level threshold in an Earth System process is likely to exist [e.g., (*20*, *21*)], the proposed planetary boundary is not placed at the position of the biophysical threshold but rather upstream of it, i.e., well before reaching the threshold. This buffer between the boundary (the end of the safe operating space—the green zone in Fig. 1) and the threshold accounts not only for uncertainty in the precise position of the threshold with respect to the control variable, but also allows society time to react to early warning signs that it may be approaching a threshold and consequent abrupt or risky change.

The developing science of early warning signs can warn of an approaching threshold or a decrease in the capability of a system to persist under changing conditions. Examples include "critical slowing down" in a process (*22*), increasing variance (*23*), and flickering between states of the system (*24*–*26*). However, for such science to be useful in a policy context, it must provide enough time for society to respond in order to steer away from an impending threshold before it is crossed (*27*, *28*). The problem of system inertia, for example, in the climate system (*18*), needs to be taken into account in assessing the time needed for society to react to early warning signs.

Not all Earth System processes included in the PB approach have singular thresholds at the global/continental/ocean basin level (*1*). Nevertheless, it is important that boundaries be established for these processes. They affect the capacity of the Earth System to persist in a Holocene-like state under changing conditions (henceforth "resilience") by regulating biogeochemical flows (e.g., the terrestrial and marine biological carbon sinks) or by providing the capacity for ecosystems to tolerate perturbations and shocks and to continue functioning under changing abiotic conditions (*29*, *30*). Examples of such processes are land-system change, freshwater use, change in biosphere integrity (rate of biodiversity loss in 1,2) and changes in other biogeochemical flows in addition to carbon (e.g., nitrogen and phosphorus). Placing boundaries for these processes is more difficult than for those with known large-scale thresholds (*21*), but is nevertheless important for maintaining the resilience of the Earth System as a whole. As indicated in Fig. 1, these processes, many of which show threshold behavior at local and regional scales, can generate feedbacks to the processes that do have large-scale thresholds. The classic example is the possible weakening of natural carbon sinks, which could further destabilize the climate system and push it closer to large thresholds (e.g, loss of the Greenland ice sheet; 18). An interesting research question of relevance to the PB approach is how small-scale regime shifts can propagate across scales and possibly lead to global-level transitions (*31*, *32*).

A zone of uncertainty, sometimes large, is associated with each of the boundaries (yellow zone in Fig. 1). This zone encapsulates both gaps and weaknesses in the scientific knowledge base and intrinsic uncertainties in the functioning of the Earth System. At the "safe" end of the zone of uncertainty, current scientific knowledge suggests that there is very low probability of crossing a critical threshold or significantly eroding the resilience of the Earth System. Beyond the "danger" end of the zone of uncertainty, current knowledge suggests a much higher probability of a change to the functioning of the Earth System that could potentially be devastating for human societies. Application of the precautionary principle dictates that the planetary boundary is set at the "safe" end of the zone of uncertainty. This doesn't mean that transgressing a boundary will instantly lead to an unwanted outcome, but that the farther the boundary is transgressed, the higher the risk of regime shifts, destabilized system processes or erosion of resilience, and the smaller the opportunities to prepare for such changes. Observations of the climate system show this principle in action by the influence of increasing atmospheric greenhouse gas concentrations on the frequency and intensity of many extreme weather events (*17*, *18*).

Linking global and regional scales

PB processes operate across scales, from ocean basins/biomes or sources/sinks, to the level of the Earth System as a whole. Here we address the sub-global aspects of the PB framework. Rockström *et al.* (*1*) estimated global boundaries only, acknowledging that the control variables for many processes are spatially heterogeneous. That is, changes in control variables at the sub-global level can influence functioning at the Earth System level, which indicates the need to define sub-global boundaries that are compatible with the global-level boundary definition. Avoiding the transgression of sub-global boundaries would thus contribute to an aggregate outcome within a planetary-level safe operating space.

We focus on the five PBs that have strong regional operating scales: biosphere integrity, biogeochemical flows (earlier termed "phosphorus (P) and nitrogen (N) cycles": 1,2), land-system change, freshwater use and atmospheric aerosol loading. Table S1 describes how transgression of any of the proposed boundaries at the sub-global level affects the Earth System at the global level.

For those processes where sub-global dynamics potentially play a critical role in global dynamics, the operational challenge is to capture the importance of sub-global change for the functioning of the Earth System. To do this, we propose the development of a two-level set of control variables and boundaries. The sub-global-level units of analysis for these six boundaries are not identical; they vary according to the role that the processes play in the Earth System: (i) changes in biosphere integrity occur at the level of land-based biomes, large freshwater ecosystems or major marine ecosystems as the largest sub-global unit; (ii) the role of direct, human-driven land-system change in biophysical climate regulation is primarily related to changes in forest biomes; (iii) freshwater flows and use occur at the largest sub-global level in the major river basins around the world; and (iv) changes in biogeochemical flows, exemplified by phosphorus and nitrogen cycling aggregate from relatively localized but very severe perturbations in intensive agricultural zones to affect global flows of nutrients. We recognize these as critical regions for Earth System functioning. Where appropriate, the updates of the individual boundaries (see below) (*33*) now contain both the globally aggregated boundary value of the control variable and its regional distribution function. Figure 2 shows the distributions and current status of the control variables for three of the boundaries where sub-global dynamics are critical—biogeochemical cycles, land-system change and freshwater use.

We emphasize that our sub-global-level focus is based on the necessity to consider this level to understand the functioning of the Earth System as a whole. The PB framework is therefore meant to complement, not replace or supersede, efforts to address local and regional environmental issues.

Updates of the individual boundaries

Brief updates of all nine of the PBs are given in this section, while more detailed descriptions of the updates for three of the PBs that have undergone more extensive revision can be found in (*33*). The geographical distribution issues discussed above are particularly important for five of the PBs, and their control variables and boundaries have been revised accordingly (Table 1). Figure 3 shows the current status of the seven boundaries that can be quantified at the global level.

Climate change

We retain the control variables and boundaries originally proposed, i.e., an atmospheric CO_2 concentration of 350 ppm and an increase in top-of-atmosphere radiative forcing of +1.0 W m^{-2} relative to pre-industrial (*1*). The radiative forcing control variable is the more inclusive and fundamental, although CO_2 is important because of its long lifetime in the atmosphere and the very large human emissions. Human-driven changes to radiative forcing include all anthropogenic factors—CO_2, other greenhouse gases, aerosols and other factors that affect the energy balance (*18*). Radiative forcing is generally the more stringent of the two boundaries although the relationship between it and CO_2 can vary through time with changes in the relative importance of the individual radiative forcing factors.

Evidence has accumulated to suggest that the zone of uncertainty for the CO_2 control variable should be narrowed from 350-550 ppm to 350-450 ppm CO_2 (*17*, *18*), while retaining the current zone of uncertainty for radiative forcing of +1.0-1.5 W m^{-2} relative to pre-industrial. Current values of the control variables are 397 ppm CO_2 (annual average concentration for 2013) (*34*) and +2.3 W m^{-2} (1.1-3.3 W m^{-2}) in 2011 relative to 1750 (*18*). Observed changes in climate at current levels of the control variables confirm the original choice of the boundary values and the narrowing of the zone of uncertainty for CO_2. For example, there has already been an increase in the intensity, frequency and duration of heatwaves globally (*35*); the number of heavy rainfall events in many regions of the world is increasing (*17*); changes in atmospheric circulation patterns have increased drought in some regions of the world (*17*); and the rate of combined mass loss from the Greenland and Antarctic ice sheets is increasing (*36*).

Changes in biosphere integrity

We propose a two-component approach, addressing two key roles of the biosphere in the Earth System. The first captures the role of genetically unique material as the "information bank" that ultimately determines the potential for life to continue to co-evolve with the abiotic component of the Earth System in the most resilient way possible. Genetic diversity provides the long-term capacity of the biosphere to persist under and adapt to abrupt and gradual abiotic change. The second captures the role of the biosphere in Earth System functioning through the value, range, distribution and relative abundance of the functional traits of the organisms present in an ecosystem or biota (*7*).

For the first role the concept of Phylogenetic Species

Variability (PSV) (*7*, *33*, *37*) would be an appropriate control variable. However, since global data are not yet available for PSV, we retain the global extinction rate as an interim control variable, although it is measured inaccurately and with a time lag. There may be a significant risk in using extinction rate as a control variable, as phylogenetic (and functional) diversity may be more sensitive to human pressures than species-level diversity (*38*). In principle, the boundary should be set at a rate of loss of PSV no greater than the rate of evolution of new PSV during the Holocene. Since that is unknown, we must fall back on the (imperfectly) known extinction rate of well-studied organisms over the past several million years—about 1 per million species-years (*39*)—and add a large uncertainty bound, raising the boundary to 10 per million species-years. The risk is that, although the Earth System can tolerate a higher-than-background level of extinctions for a time, we do not know what levels of, or types of, biodiversity loss may possibly trigger nonlinear or irreversible changes to the Earth System.

The second control variable aims to capture the role of the biosphere in Earth System functioning, and measures loss of biodiversity components at both global and biome/large ecosystem levels. Although several variables have been developed at local scales for measuring functional diversity [e.g., (*40*)], finding an appropriate control variable at regional or global levels is challenging. For the present we propose an interim control variable: Biodiversity Intactness Index (BII) (*41*). BII assesses change in population abundance as a result of human impacts, such as land or resource use, across a wide range of taxa and functional groups at a biome or ecosystem level using pre-industrial era abundance as a reference point. The index typically ranges from 100% (abundances across all functional groups at pre-industrial levels) to lower values that reflect the extent and degree of human modification of populations of plants and animals. BII values for particular functional groups can go above 100% if human modifications to ecosystems lead to increases in the abundance of those species.
Due to a lack of evidence on the relationship between BII and Earth System responses, we propose a preliminary boundary at 90% of the BII but with a very large uncertainty range (90-30%) that reflects the large gaps in our knowledge about the BII-Earth System functioning relationship (*42*, *43*). BII has been so far applied to southern Africa's terrestrial biomes only (cf. fig. S3 for an estimation of aggregated human pressures on the terrestrial biosphere globally), where the index (not yet disaggregated to functional groups) was estimated to be 84%. BII ranged from 69 to 91% for the seven countries where it has been applied (*41*). Observations across these countries suggest that decreases in BII adequately capture increasing levels of ecosystem degradation, defined as land uses that do not alter the land-cover type but lead to a persistent loss in ecosystem productivity (*41*).

In addition to further work on functional measures such as BII, in the longer term the concept of biome integrity—the functioning and persistence of biomes at broad scales (*7*)—offers a promising approach, and, with further research, could provide a set of operational control variables (one per biome) that is appropriate, robust, and scientifically based.

Stratospheric ozone depletion

We retain the original control variable (O_3 concentration in DU (Dobson Units) and boundary (275 DU). This boundary is only transgressed over Antarctica in the austral spring, when O_3 concentration drops to about 200 DU (*44*). However, the minimum O_3 concentration has been steady for about 15 years and is expected to rise over the coming decades as the ozone hole is repaired after the phasing out of ozone depleting substances. This is an example where, after a boundary has been transgressed regionally, humanity has taken effective action to return the process back to within the boundary.

Ocean acidification

This boundary is intimately linked with one of the control variables, CO_2, for the climate change PB. The concentration of free H^+ ions in the surface ocean has increased by about 30% over the last 200 years due to the increase in atmospheric CO_2 (*45*). This, in turn, influences carbonate chemistry in surface ocean waters. Specifically, it lowers the saturation state of aragonite (Ω_{arag}), a form of calcium carbonate formed by many marine organisms. At $\Omega_{arag} < 1$, aragonite will dissolve. No new evidence has emerged to suggest that the originally proposed boundary (≥80% of the preindustrial average annual global Ω_{arag}) should be adjusted, although geographical heterogeneity in Ω_{arag} is important in monitoring the state of the boundary around the world's oceans (fig. S4). Currently, Ω_{arag} is approximately equal to 84% of the pre-industrial value (*46*). This boundary would not be transgressed if the climate change boundary of 350 ppm CO_2 were to be respected.

Biogeochemical flows

The original boundary was formulated for phosphorus (P) and nitrogen (N) only, but we now propose a more generic PB to encompass human influence on biogeochemical flows in general. While the carbon cycle is covered in the climate change boundary, other elements, such as silicon (*47*, *48*) are also important for Earth System functioning. Furthermore, there is increasing evidence that ratios between elements in the environment may have impacts on biodiversity on land and in the sea (*49*–*51*). Thus, we may ultimately need to develop PBs for other elements and their ratios, although for now we focus on P and N only.

A two-level approach is now proposed for the P component of the biogeochemical flows boundary (see also SM). The original global-level boundary, based on the prevention of a large-scale ocean anoxic event, is retained with the proposed boundary set at a sustained flow of 11 Tg P y^{-1} from freshwater systems into the ocean. Based on the analysis of Carpenter and Bennett (*3*), we now propose an additional regional-level P boundary, designed to avert widespread eutrophication of freshwater systems, at a flow of 6.2 Tg P y^{-1} (from fertilizers (mined P) to erodible soils.

Given that the addition of P to regional watersheds is almost entirely via fertilizers, the regional-level boundary applies primarily to the world's croplands. The current global rate of application of P in fertilizers to croplands is 14.2 Tg P y^{-1} (*52*, *53*). Observations point towards a few agricultural regions of very high P application rates as the main contributors to the transgression of this boundary (Fig. 2 and fig. S5A), and suggest that a redistribution of P from areas where it is currently in excess to areas where the soil is naturally P-poor may simultaneously boost global crop production and reduce the transgression of the regional-level P boundary (*3*, *52*, *54*).

The N boundary has been taken from the comprehensive analysis of De Vries *et al.* (*5*), which proposed a PB for eutrophication of aquatic ecosystems of 62 Tg N yr^{-1} from industrial and intentional biological N fixation, using the most stringent water quality criterion. As for the P boundary, a few agricultural regions of very high N application rates are the main contributors to the transgression of this boundary (Fig. 2 and fig. S5B). This suggests that a redistribution of N could simultaneously boost global crop production and reduce the transgression of the regional-level boundary.

Because the major anthropogenic perturbation of both the N and P cycles arises from fertilizer application, we can analyze the links between the independently determined N and P boundaries in an integrated way based on the N:P ratio in the growing plant tissue of agricultural crops. Applying this ratio, which is on average 11.8 (*55*), to the P boundary (6.2 Tg P yr^{-1}) gives an N boundary of 73 Tg N yr^{-1}. Conversely, applying the ratio to the N boundary (62 Tg N yr^{-1}) gives a P boundary of 5.3 Tg P yr^{-1}. The small differences between the boundaries derived using the N:P ratio and those calculated independently, which are likely non-significant differences given the precision of the data available for the calculations, show the internal consistency in our approach to the biogeochemical boundaries.

More detail on the development of the P and N boundaries is given in 33, where we also emphasize that the proposed P and N boundaries may be larger for an optimal allocation of N (and P) over the globe.

Land-system change

The updated biosphere integrity boundary provides a significant constraint on the amount and pattern of land-system change in all terrestrial biomes—forests, woodlands, savannas, grasslands, shrublands, tundra, etc. The land-system change boundary is now focused more tightly on a specific constraint: the biogeophysical processes in land systems that directly regulate climate—exchange of energy, water and momentum between the land surface and the atmosphere. The control variable has been changed from the amount of cropland to the amount of forest cover remaining, as the three major forest biomes—tropical, temperate and boreal—play a stronger role in land surface-climate coupling than other biomes (*56*, *57*). In particular, we focus on those land-system changes that can influence the climate in regions beyond the region where the land-system change occurred.

Of the forest biomes, tropical forests have significant feedbacks to climate via changes in evapotranspiration when they are converted to non-forested systems, while changes in the distribution of boreal forests affect the albedo of the land surface and hence regional energy exchange. Both have strong regional and global teleconnections. The biome-level boundary for these two types of forest have been set at 85% (Table 1; SM) while the boundary for temperate forests has been proposed at 50% of potential forest cover, because changes to temperate forests are estimated to have weaker influences on the climate system at the global level than changes to the other two major forest biomes (*56*). These boundaries would almost surely be met if the proposed biosphere integrity boundary of 90% BII were respected.

Estimates of the current status of the land-system change boundary are given in Figs. 2 and 3 and fig. S6 and in (*58*).

Freshwater use

The revised freshwater use boundary has retained consumptive use of blue water [from rivers, lakes, reservoirs and renewable groundwater stores (*59*)] as the global-level control variable and 4000 km^3/yr as the value of the boundary. This PB may be somewhat higher or lower depending on rivers' ecological flow requirements (*6*). Therefore, we here report a new assessment to complement the PB with a basin-scale boundary for the maximum rate of blue water withdrawal along rivers, based on the amount of water required in the river system to avoid regime shifts in the functioning of flow-dependent ecosystems. We base our control variable on the concept of environmental water flows (EWF), which defines the level of river flows for different hydrological characteristics of river basins adequate to maintain a fair-to-good ecosystem state (*60*–*62*).

The Variable Monthly Flow (VMF) method (*33*, *63*) was used to calculate the basin-scale boundary for water. This method takes account of intra-annual variability by classifying flow regimes into high-, intermediate- and low-flow months and allocating EWF as a percentage of the mean monthly flow (MMF). Based on this analysis, the zones of uncertainty for the river-basin scale water boundary were set at 25 to 55% of MMF for the low-flow regime, 40-70% for the intermediate-flow regime, and 55-85% for the high-flow regime (table S2). The boundaries were set at the lower end of the uncertainty ranges that encompass average monthly EWF. Our new estimates of the current status of the water use boundary—computed based on grid cell-specific estimates of agricultural, industrial and domestic water withdrawals—are shown in Figs. 2 and 3, with details in figs. S7 and S8.

Atmospheric aerosol loading: Aerosols have well-known, serious human health impacts, leading to about 7.2 million deaths per year (*64*). They also affect the functioning of the Earth System in many ways (*65*) (fig. S9). Here we focus on the impact of aerosols on regional ocean-atmosphere circulation as the rationale for a separate aerosols boundary. We adopt aerosol optical depth (AOD,33) as the control variable and use the South Asian monsoon as a case study, based on the potential of widespread aerosol loading over the Indian subcontinent to switch the monsoon system to a drier state. The background AOD over South Asia is ~0.15 and can be as high as 0.4 during volcanic events (*66*). Emissions of black carbon and organic carbon from cooking and heating with biofuels and from diesel transportation, and emission of sulfates and nitrates from fossil fuel combustion, can increase seasonal mean AODs to as high as 0.4 (larger during volcanic periods), leading to decreases of 10% to 15% of incident solar radiation at the surface (fig. S9). A significant decrease in monsoon activity is likely around an AOD of 0.50, an increase of 0.35 above the background (*67*). Taking a precautionary approach towards uncertainties surrounding the position of the tipping point, we propose a boundary at an AOD of 0.25 (an increase due to human activities of 0.1), with a zone of uncertainty of 0.25 to 0.50. The annual mean AOD is currently about 0.3 (*66*), within the zone of uncertainty.

Introduction of novel entities

We define novel entities as new substances, new forms of existing substances and modified life-forms that have the potential for unwanted geophysical and/or biological effects. Anthropogenic introduction of novel entities to the environment are of concern at the global level when these entities exhibit (i) persistence, (ii) mobility across scales with consequent widespread distributions, and (iii) potential impacts on vital Earth System processes or sub-systems. These potentially include chemicals and other new types of engineered materials/organisms [e.g. (*68*–*71*)] not previously known to the Earth System as well as naturally occurring elements (for example heavy metals) mobilized by anthropogenic activities. The risks associated with the introduction of novel entities into the Earth System are exemplified by the release of CFCs (chlorofluorocarbons), which are very useful synthetic chemicals that were thought to be harmless but had unexpected, dramatic impacts on the stratospheric ozone layer. In effect, humanity is repeatedly running such global-scale experiments, but not yet applying the insights from previous experience to new applications (*72*, *73*).

Today there are more than 100,000 substances in global commerce (*74*). If nanomaterials and plastic polymers that degrade to microplastics are included, the list is even longer. There is also a "chemical intensification" due to the rapidly increasing global production of chemicals, the expanding worldwide distribution as chemical products or in consumer goods, and the extensive global trade in chemical wastes (*75*).

In recent years there has been a growing debate about the global scale effects of chemical pollution, leading to calls for the definition of criteria to identify the kinds of chemical substances that are likely to be globally problematic (*76*, *77*). Persson *et al.* (*73*) proposed that there are three conditions that need to be fulfilled in order for a chemical to pose a threat to the Earth System: (i) the chemical has an unknown disruptive effect on a vital Earth System process; (ii) the disruptive effect is not discovered until it is a problem at the global scale; and (iii) the effect is not readily reversible. The challenge to the research community is to develop the knowledge base that allows the screening of chemicals, before they are released into the environment, for properties that may predispose them towards becoming global problems.

As a first step towards meeting this challenge, the three conditions outlined above have been used as the basis for identifying scenarios of chemical pollution that fulfill the conditions, and as a next step, for pinpointing chemical profiles that fit the scenarios (*28*). This proposal constitutes a first attempt at adding the Earth System perspective when assessing hazard and risk of chemicals and offers a vision for a systematic approach to a complex management situation with many unknowns.

Despite this progress in developing an Earth System-oriented approach, there is not yet an aggregate, global-level analysis of chemical pollution on which to base a control variable or a boundary value. It may also serve little purpose to define boundary values and control variables for a planetary boundary of this complexity. Nevertheless, there is a potential threat from novel entities to disrupt the functioning of Earth System and society needs to learn how to mitigate these unknown risks and manage chemicals under uncertainty (*28*, *73*).

Some precautionary and preventive actions can be considered. These may include stronger focus on green chemistry (*78*), finding synergies with risk-reducing interventions in other fields such as occupational health (*79*), paying more attention to learning from earlier mistakes (*80*, *81*), as well as investing in science to better understand and monitor vital Earth System processes in order to be able to detect disruptive effects from novel entities as early as possible.

Hierarchy of boundaries

An analysis of the many interactions among the boundaries (table S3 and fig. S10) suggests that two of them—climate change and biosphere integrity—are highly integrated, emergent system-level phenomena that are connected to all of the other PBs. They operate at the level of the whole Earth System (*7*), and have co-evolved for nearly 4 billion years (*82*). They are regulated by the other boundaries and, on the other hand, provide the planetary-level overarching systems within which the other boundary processes operate. Furthermore, large changes in the climate or in biosphere integrity would likely, on their own, push the Earth System out of the Holocene state. In fact, transitions between time periods in Earth history have often been delineated by significant shifts in climate, the biosphere, or both (*82*, *83*).

These observations suggest a two-level hierarchy of boundaries, in which climate change and biosphere integrity should be recognized as core planetary boundaries through which the other boundaries operate. The crossing of one or more of all of the other boundaries may seriously affect human wellbeing, and may predispose the transgression of a core boundary(ies), but does not by itself lead to a new state of the Earth System. This hierarchical approach to classifying the boundaries becomes clearer by examining in more detail the roles of climate and biosphere integrity in the functioning of the Earth System.

The climate system is a manifestation of the amount, distribution and net balance of energy at the Earth's surface. The total amount of energy sets the overall conditions for life. In Earth's current climate a range of global surface temperatures and atmospheric pressures allows the three phases of water to be present simultaneously, with ice and water vapor playing critical roles in the physical feedbacks of the climate system. The distribution of energy by latitude, over the land and sea surfaces and within the ocean, plays a major role in the circulation of the two great fluids, the ocean and the atmosphere. These systemic physical characteristics are key spatial determinants of the distribution of the biota and the structure and functioning of ecosystems, and are controllers of biogeochemical flows.

Biosphere integrity is also crucial to Earth System functioning, where the biosphere is defined as the totality of all ecosystems (terrestrial, freshwater and marine) on Earth and their biota (*32*). These ecosystems and biota play a critical role in determining the state of the Earth System, regulating its material and energy flows and its responses to abrupt and gradual change (*7*). Diversity in the biosphere provides resilience to terrestrial and marine ecosystems (*83*, *84*). The biosphere not only interacts with the other planetary boundaries, but also increases the capacity of the Earth System to persist in a given state under changes in these other boundaries. The ultimate basis for the many roles that the biosphere plays in Earth System dynamics is the genetic code of the biota, the basic information bank that defines the biosphere's functional role and its capacity to innovate and persist into the future.

Planetary boundaries in a societal context

A proposed approach for Sustainable Development Goals (*85*) argues that the stable functioning of the Earth System is a prerequisite for thriving societies around the world. This approach implies that the PB framework, or something like it, will need to be implemented alongside the achievement of targets aimed at more immediate human needs, such as provision of clean, affordable and accessible energy and the adequate supply of food. World development within the biophysical limits of a stable Earth System has always been a necessity [e.g., (*86*, *87*)]. However, only recently, for a number of reasons, has it become possible to identify, evaluate and quantify risks of abrupt planetary- and biome-level shifts due to overshoot of key Earth System parameters: (i) the emergence of global change- and Earth System- thinking (*88*), (ii) the rise of 'the Planetary' as a relevant level of complex system understanding (*89*–*92*), and (iii) observable impacts of the rapid increase in human pressures on the planet (*16*).

The PB approach is embedded in this emerging social context, but it does not suggest *how* to maneuver within the safe operating space in the quest for global sustainability. For example, the PB framework does not as yet account for the regional distribution of the impact, nor of its historical patterns. Nor does the PB framework take into account the deeper issues of equity and causation. The current levels of the boundary processes, and the transgressions of boundaries that have already occurred, are unevenly caused by different human societies and different social groups. The wealth benefits that these transgressions have brought are also unevenly distributed socially and geographically. It is easy to foresee that uneven distribution of causation and benefits will continue, and these differentials must surely be addressed for a Holocene-like Earth System state to be successfully legitimated and maintained. However, the PB framework as currently construed provides no guidance as to how this may be achieved (although some potential synergies have been noted, see 54) and it cannot readily be used to make choices between pathways for piecemeal maneuvering within the safe operating space or more radical shifts of global governance (*93*).

The nature of the PB framework implies that two important cautions should be observed when application of the framework to policy or management is proposed:

Boundary interactions

The planetary boundaries framework arises from the scientific evidence that Earth is a single complex, integrated system—that is, the boundaries operate as an interdependent set [e.g., (*94*)] (table S1 and fig. S10). While a systematic, quantitative analysis of interactions among all of the processes for which boundaries are proposed remains beyond the scope of current modeling and observational capacity, the Earth System clearly operates in well-defined states in which these processes and their interactions can create stabilizing or destabilizing feedbacks (*16*, *90*, *95*). This has profound implications for global sustainability, as it emphasizes the need to address multiple interacting environmental processes simultaneously (e.g., stabilizing the climate system requires sustainable forest management, stable ocean ecosystems, etc).

Scale

The PB framework is not designed to be "downscaled" or "disaggregated" to smaller levels, such as nations or local communities. That said, the PB framework recognizes the importance of changes at the level of sub-systems in the Earth System (e.g., biomes or large river basins) on the functioning of the Earth System as a whole. Also, there are strong arguments for an integrated approach coupling boundary definitions at regional and global levels with development goals to enable the application of "PB thinking" at levels (nations, basins, regions) where policy action most commonly occurs [e.g., (*85*, *96*)].

This update of the PB framework is one step on a longer-term evolution of scientific knowledge to inform and support global sustainability goals and pathways. This evolution is needed more than ever before; there are severe implementation gaps in many global environmental policies relating to the PB issues, where problematic trends are not being halted or reversed despite international consensus about the urgency of the problems. The prospect of tighter resource constraints and rising environmental hazards is also unavoidably turning the focus onto global social equity and the planetary stewardship of the Earth's life support system. There is a need for a truly global evidence base, with much greater integration among issues, in order to respond to these global challenges. New research initiatives [e.g., Future Earth (www.futureearth.org)] provide evidence that science can respond to this need by applying Earth System research to advance a new generation of integrated global analyses and to explore options for transformations towards sustainability. This is a clear sign that, as the risks of the Anthropocene to human wellbeing become clearer, research is maturing to a point where a systemic step-change is possible—and necessary—in exploring and defining a safe and just planetary operating space for the further development of human societies.

Methods summary

Our approach to building the planetary boundaries framework is described above. We have implemented the framework through an expert assessment and synthesis of the scientific knowledge of intrinsic biophysical processes that regulate the stability of the Earth System. Our precautionary approach is based on the maintenance of a Holocene-like state of the ES, and on an assessment of the level of human-driven change that would risk destabilizing this state. For the climate change PB, there is already much literature on which to base such an assessment. For others, such as stratospheric ozone, ocean acidification, extinction rates, and P and N cycles, we have used estimates of pre-industrial values of the control variable as a Holocene baseline. Where large, undesirable thresholds exist and have been studied (e.g., polar ice sheets, Amazon rainforest, aragonite dissolution, atmospheric aerosols and the South Asian monsoon), quantitative boundaries can be readily proposed. For others, where the focus is on erosion of ES resilience, the boundaries are more difficult (but not impossible) to quantify, as reflected in larger uncertainty zones.

We used large-scale assessments of the impact of human activities on ES functioning [e.g., IPCC (*17*, *18*), the IGBP synthesis (*16*), chemicals (*75*, *80*)] as sources of community-level understanding on which to propose PBs. Our update has also relied on post-2009 assessments of individual boundaries by the relevant expert research communities; examples include phosphorus (*3*), nitrogen (*5*), biosphere integrity (*7*), freshwater use (*5*, *63*), and novel entities [with a focus on chemicals, (*28*, *73*)]. Finally, some new analyses have been undertaken specifically for this paper: (i) a freshwater use PB based on the environmental water flow (EWF) approach (*33*, *63*); (ii) the linkage of the phosphorus and nitrogen boundaries via the N:P ratio in growing crop tissue (*33*); and (iii) the use of major forest biomes as the basis for the land-system change PB (*33*).

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ACKNOWLEDGMENTS

We thank J. Foley and N. Ramunkutty for contributions to the land-system change boundary; A. Pastor for analytical work on the PB for freshwater; B. Armstrong, C. Butler, T. McMichael, and A. Woodward for contributions to the novel entities boundary; and B. Scholes for comments on an earlier version of the manuscript. Data associated with the paper are located at the Stockholm Resilience Centre, Sweden (http://www.stockholmresilience.org/21/research/research-programmes/planetary-boundaries.html). The planetary boundaries research at the Stockholm Resilience Centre is made possible through a core grant from MISTRA (Swedish Foundation for Strategic Environmental Research). S.E.C. is supported by the Swedish Research Council, R.B. is supported by a Branco Weiss Fellowship, C.F. is supported by the Family Erling Persson Academy Programme on Global Economic Dynamics and the Biosphere, I.F. is supported by the Stordalen Foundation (Norway), and S.R.C. and V.R. are supported by the U.S. National Science Foundation

SUPPLEMENTARY MATERIALS

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11 August 2014; accepted 8 January 2015
Published online 15 January 2015; 10.1126/science.1259855

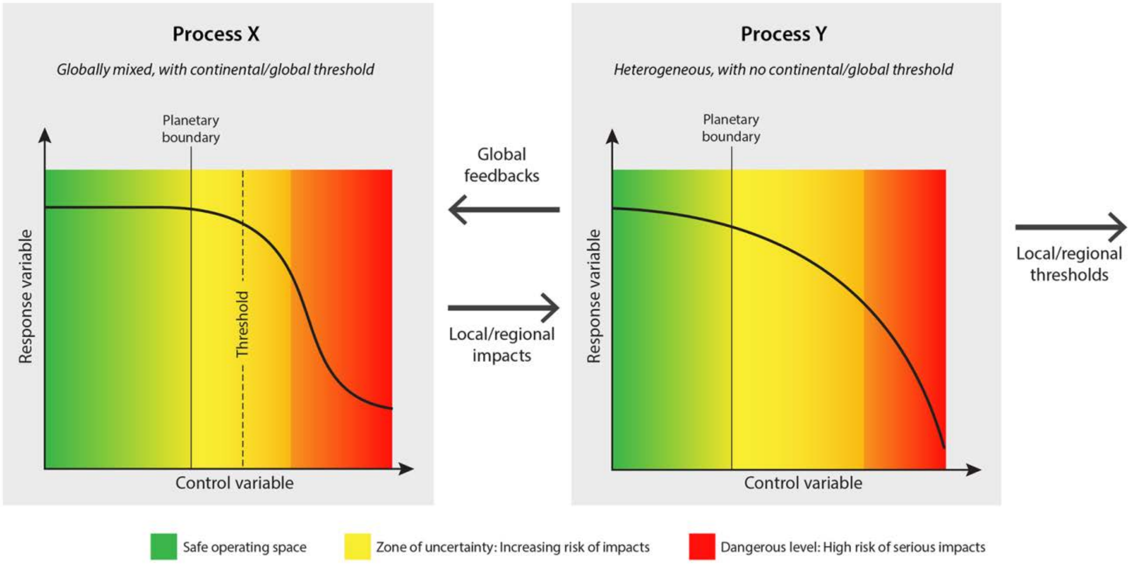

Fig. 1. The conceptual framework for the planetary boundaries approach, showing the safe operating space, the zone of uncertainty, the position of the threshold (where one is likely to exist) and the area of high risk. Modified from (*1*).

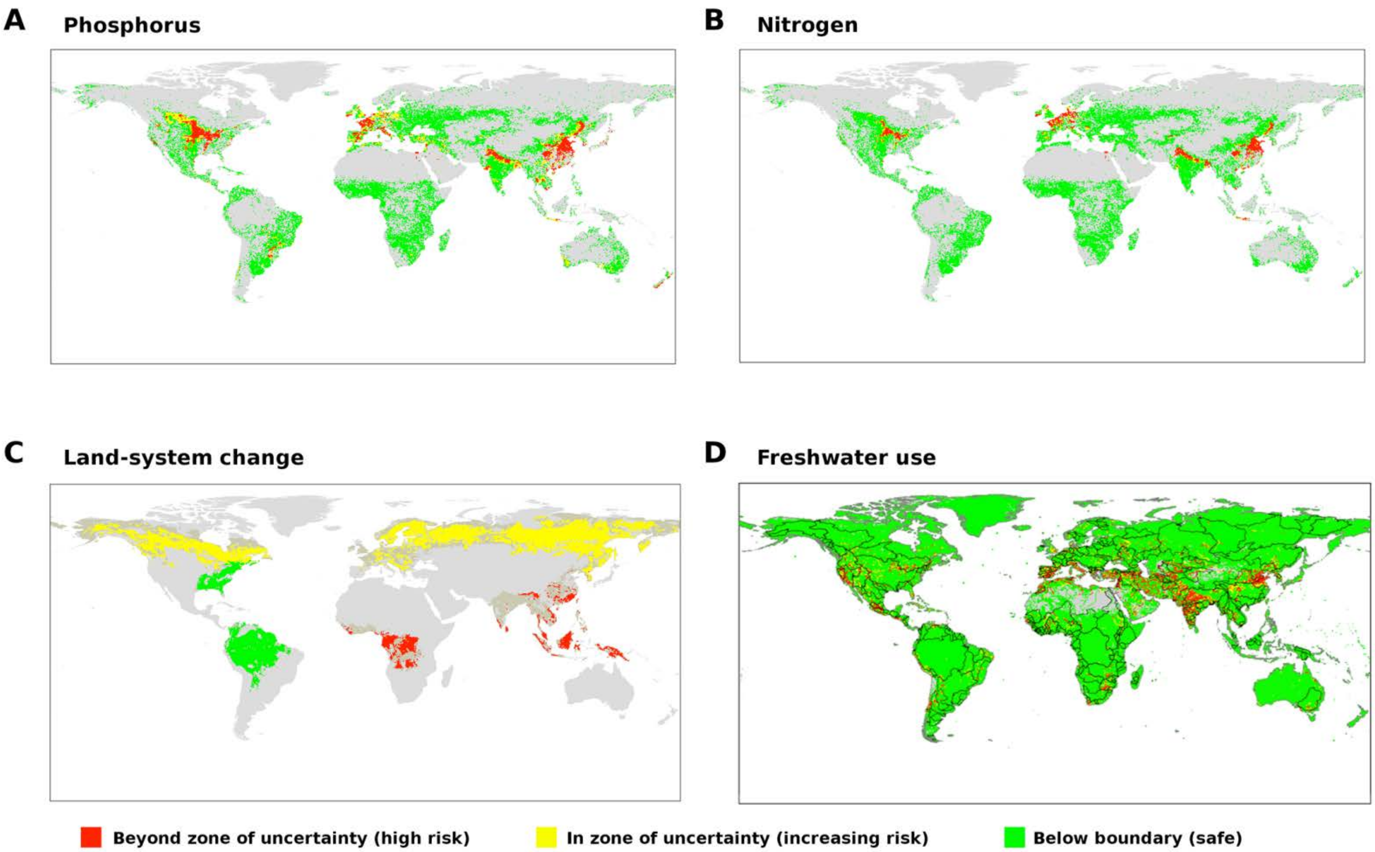

Fig. 2. The global distributions and current status of the control variables for (**A**) biogeochemical flows – P, (**B**) biogeochemical flows – N, (**C**) land-system change, and (**D**) freshwater use. In each panel, green areas are within the boundary (safe); yellow areas are within the zone of uncertainty (increasing risk); and red areas are beyond the zone of uncertainty (high risk). Gray areas in (A) and (B) are areas where P and N fertilizers are not applied, in (C) are areas not covered by major forest biomes, and in (D) are areas where river flow is very low so that environmental flows are not allocated. See Table 1 for values of the boundaries and their zones of uncertainty, and 33 for more details on methods and results.

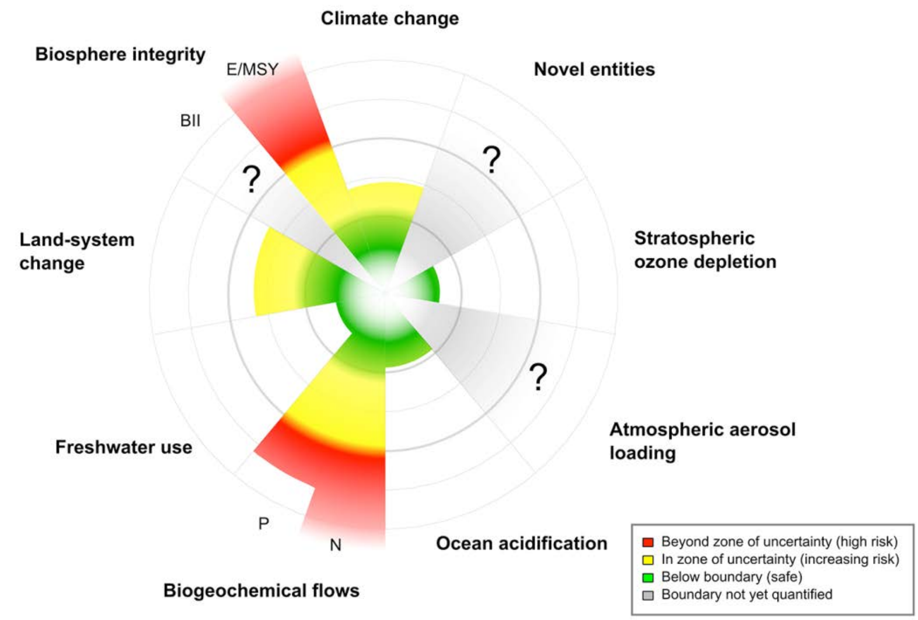

Fig. 3. The current status of the control variables for seven of the nine planetary boundaries. Green zone is the safe operating space (below the boundary), yellow represents the zone of uncertainty (increasing risk), and red is the high-risk zone. The planetary boundary itself lies at the inner heavy circle. The control variables have been normalized for the zone of uncertainty (between the two heavy circles); the center of the figure therefore does not represent values of 0 for the control variables. The control variable shown for climate change is atmospheric CO_2 concentration. Processes for which global-level boundaries cannot yet be quantified are represented by gray wedges; these are atmospheric aerosol loading, novel entities and the functional role of biosphere integrity. Modified from (*1*).

Table 1. The updated control variables and their current values, along with the proposed boundaries and zones of uncertainty, for all nine planetary boundaries.

Earth system process	**Control variable(s)**	**Planetary boundary (zone of uncertainty)**	**Current value of control variable**
Climate change (R2009: same)	Atmospheric CO_2 concentration, ppm Energy imbalance at top-of-atmosphere, W m^{-2}	350 ppm CO_2 (350-450 ppm) Energy imbalance: +1.0 W m^{-2} (+1.0-1.5 W m^{-2})	396.5 ppm CO_2 2.3 W m^{-2} (1.1-3.3 W m^{-2})
Change in biosphere integrity (R2009: Rate of biodiversity loss)	Genetic diversity: Extinction rate Functional: diversity: Biodiversity Intactness Index (BII) ***Note: These are interim control variables until more appropriate ones are developed.***	Genetic: < 10 E/MSY (10-100 E/MSY) but with an aspirational goal of ca. 1 M/ESY* (the background rate of extinction loss).* E/MSY = extinctions per million species-years Functional: Maintain BII at 90% (90-30%) or above, assessed geographically by biomes/large regional areas (e.g. southern Africa), major marine ecosystems (e.g., coral reefs) or by large functional groups	100-1000 E/MSY 84%, applied to southern Africa only
Stratospheric ozone depletion (R2009: same)	Stratospheric O_3 concentration, DU	<5% reduction from pre-industrial level of 290 DU (5%–10%), assessed by latitude	Only transgressed over Antarctica in Austral spring (~200 DU)
Ocean acidification (R2009: same)	Carbonate ion concentration, average global surface ocean saturation state with respect to aragonite (Ω_{arag})	≥80% of the pre-industrial aragonite saturation state of mean surface ocean, including natural diel and seasonal variability (≥80%– ≥70%)	~84% of the pre-industrial aragonite saturation state
Biogeochemical flows: (P and N cycles) [R2009: Biogeochemical flows: (interference with P and N cycles)]	*P cycle:* Global: P flow from freshwater systems into the ocean Regional: P flow from fertilizers to erodible soils *N cycle:* Global: Industrial and intentional biological fixation of N	*P cycle:* Global: 11 Tg P yr^{-1} (11-100 Tg P yr^{-1}) Regional: 6.2 Tg yr^{-1} mined and applied to erodible (agricultural) soils (6.2-11.2 Tg yr^{-1}). Boundary is a global average but regional distribution is critical for impacts. 62 Tg N yr^{-1} (62-82 Tg N yr^{-1}). Boundary acts as a global 'valve' limiting introduction of new reactive N to Earth System, but regional distribution of fertilizer N is critical for impacts.	 ~22 Tg P yr^{-1} ~14 Tg P yr^{-1} ~150 Tg N yr^{-1}
Land-system change (R2009: same)	Global: area of forested land as % of original forest cover Biome: area of forested land as % of potential forest	Global: 75% (75-54%) Values are a weighted average of the three individual biome boundaries and their uncertainty zones Biome: Tropical: 85% (85-60%) Temperate: 50% (50-30%) Boreal: 85% (85-60%)	62%
Freshwater use (R2009: Global freshwater use)	Global: Maximum amount of consumptive blue water use (km^3 yr^{-1}) Basin: Blue water withdrawal as % of mean monthly river flow	Global: 4000 km^3 yr^{-1} (4000-6000 km^3 yr^{-1}) Basin: Maximum monthly withdrawal as a percentage of mean monthly river flow. For low-flow months: 25% (25-55%); for intermediate-flow months: 30% (30-60%); for high-flow months: 55% (55-85%)	~2600 km^3 yr^{-1}

Atmospheric aerosol loading (R2009: same)	<u>Global</u>: Aerosol Optical Depth (AOD), but much regional variation <u>Regional:</u> AOD as a seasonal average over a region. South Asian Monsoon used as a case study	<u>Regional</u>: (South Asian Monsoon as a case study): anthropogenic total (absorbing and scattering) AOD over Indian subcontinent of 0.25 (0.25-0.50); absorbing (warming) AOD less than 10% of total AOD	0.30 AOD, over South Asian region
Introduction of novel entities (R2009: Chemical pollution)	***<u>No control variable currently defined</u>***	***No boundary currently identified, but see boundary for stratospheric ozone for an example of a boundary related to a novel entity (CFCs)***	

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Total number of authors:
13

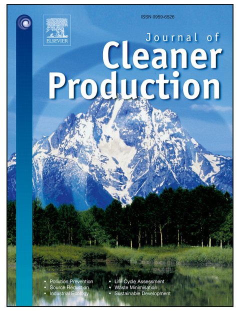
Published in:
Journal of Cleaner Production

Link to article, DOI:
10.1016/j.jclepro.2019.118271

Publication date:
2019

Document Version
Peer reviewed version

Journal Pre-proof



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PII: S0959-6526(19)33141-5

DOI: https://doi.org/10.1016/j.jclepro.2019.118271

Reference: JCLP 118271

To appear in: *Journal of Cleaner Production*

Received Date: 28 October 2018

Revised Date: 30 August 2019

Accepted Date: 2 September 2019

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Keywords Circular strategies framework, closed loop, resource productivity, manufacturing companies, innovation.

Acknowledgements

This article is one of the outcomes of the research project CIRCit (Circular Economy Integration in the Nordic Industry for Enhanced Sustainability and Competitiveness), which is part of the Nordic Green Growth Research and Innovation Programme (grant numbers: 83144) and funded by NordForsk, Nordic Energy Research, and Nordic Innovation. We would also like to thank the companies participating in the CIRCit project and the anonymous reviewers whose thoughtful feedback aided the development of this work.

Developing a circular strategies framework for manufacturing companies to support circular economy-oriented innovation

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1. Introduction

The linear economy is frequently characterised by the presence of structural waste: instances where components, products or materials reach their end-of-use/life prematurely, or where their capacity for value creation is underutilised. To address this, the circular economy (CE) concept proposes a range of efficiency and productivity enhancing activities collectively known as circular strategies, such as reduce, reuse, repair, recycle, restore, cascading, etc (EMF, 2013). In this sense, CE is an umbrella concept: it groups a range of sub-concepts and imbues them with a new meaning by highlighting a shared feature of the sub-concepts (Blomsma and Brennan 2017). This new meaning revolves around the notion that through the application of circular strategies both more value can be created (EMF, 2013) as well as value loss and destruction reduced (Murray et al., 2015).

Although CE has widely been recognised as an idea with potential merit, it has yet to be widely implemented and embedded within business and industry (Haas et al., 2015; Circle Economy 2019). This is in line with the progression of umbrella concepts: when the transformative potential of an idea has been recognised, the attention then turns to operationalising it through frameworks, tools, methods and approaches. This, in turn, allows for further examination of the concept.

For CE this means that there is currently a focus on developing CE transition methodology. This is taking place in a number of aspects relevant for Circular Oriented Innovation (COI) (Brown et al. 2019), such as in business models (Bocken and Antikanen 2018; Pieroni et al. 2019; Rosa et al. 2019), metrics and assessment (Kravchenko et al. 2019; Moraga et al. 2019; Saidani et al. 2019), product design (Moreno et al. 2016; Den Hollander et al. 2017) and the creation of organisational capabilities such as experimentation, value chain innovation and other human factors (Weissbrod and Bocken 2017; Chiappetta Jabbour et al. 2019; Nilsson-Lindén et al. 2019).

Previous academic work focuses on answering 'what' or 'how' to promote COI (Guzzo et al. 2019; Mendoza et al. 2017). However, supporting the early stages of COI through the establishment of a CE vision, i.e. answering

why to perform COI, has so far achieved relatively little scholarly attention. Finding the 'why' for a CE transition, requires understanding the type of structural waste in the system, which can be accomplished with a systemic analysis/diagnosis across life cycle stages and various business processes and knowledge areas. This requires various actors within and across business to define and explore problem and solution spaces together (Brown et al., 2019). Specifically, in COI a high-level conceptual understanding of CE needs to be translated into a vision that is useful and meaningful on the level of decision making (Hoffman, 2003; Boons and Howard-Grenville, 2009; Lindkvist and Baumann, 2014). The importance of a shared vision in innovation projects has long since been acknowledged (Pearce and Ensley, 2004; Bititci et al., 2004), and it has been posited to be relevant for both inter and intra organisational COI efforts (Brown et al., 2019).

Currently, there exists a range of frameworks that could potentially be drawn from to support CE visioning. These take the form of circular strategies frameworks, such as the ReSOLVE framework (EMF, 2015), the Performance Economy (Stahel ,2006), Cradle-to-Cradle™ (Braungart and McDonough, 2002), and the Waste Hierarchy (EC, 2008), but also the Ricoh Comet Circle™ (Ricoh, 2018), the Seven Fronts of Mount Sustainability (Interface, 2018). Importantly, these frameworks can be seen as the visual representations of a vision for how to operate in a CE, since they select, name and organise circular strategies seen as relevant, such that their relationship becomes apparent.

However, Mendoza et al. (2017), Reike et al. (2017) and Blomsma (2018) observed that such circular strategies frameworks can identify or emphasise different (groups of) circular strategies, which can be linked to addressing different types of structural waste. As such, there is a risk that they do not include circular strategies with transformative potential for a particular context. Moreover, Blomsma (2018) points out that little work has been done with regard to ensuring that frameworks are seen as relevant and useful by their intended audiences. For these reasons, there is scope to further develop these frameworks to support visioning in COI. Mendoza et al. (2017), Niero and Hauschild (2017) and Blomsma (2018) therefore call for the development of such frameworks within academia.

This paper answers this call and addresses the question of how to develop circular strategies frameworks such that they are relevant for their intended audiences, in a manner that points to the transformative potential of CE and that assists with unpacking the complexity associated with COI. With this, this paper contributes to the body of work that develops CE transition methodology, focussing on the early stages of COI and engaging the affected audiences in a transdisciplinary approach (Sakao and Brambila, 2018).

As an illustrative case, we develop a circular strategies framework for manufacturing companies1. Manufacturing companies were chosen as the focus as they are important users of materials and energy, produce significant amounts of byproducts traditionally regarded as waste, and form an important employment sector2 and contributor to GDP (Rashid et al., 2013). In addition, manufacturing companies play an important role in the creation of value to their customers and therefore have great potential to decouple this value provision from linear resource consumption.

After clarifying the research gap in the background section and exploring the shortfalls of current circular strategies frameworks to support COI within manufacturing, we continue with setting out the methodology applied in this paper. In the following sections we present the development of the criteria used for designing the new framework and explain the relevant details and outcomes of each subsequent development phase. Furthermore, in section 6, we provide an example of application of the framework in COI. We close with a discussion of the contributions of this paper and directions for further work.

[1] We use the expression *manufacturing companies* to refer to secondary manufacturing, as opposed to primary production. Moreover, these companies are not contract manufacturers, but have a degree of control over their supply chain.

[2] Sector, as used here, refers to an area of economic activity such as food, medicine, construction, etc. See: https://unstats.un.org/unsd/classifications/.

2. Background and research clarification

Describing the complete landscape of circular strategies frameworks is beyond the scope of this paper. However, here we provide an overview of the current landscape of circular strategies framework, through offering a typology of five classes of frameworks. The first four classes describe a continuum where the scope becomes increasingly smaller: (1) the macro level of industrial systems or economies; (2) the meso level of sectors, materials and business types; (3) the micro level of companies; and (4) the nano level covering product (groups) (Saidani et al., 2017). The fifth level adds the layer of (5) networked and regional approaches, through which the other four levels are connected. See Figure 1.

Overview of the landscape of circular strategies frameworks

Figure 1. Schematic illustrating the coverage of frameworks on the macro-meso-micro-nano scale, and their relationship with frameworks covering networked and regional approaches.

Considering the landscape of current circular strategies frameworks, a number of observations can be made that explain why current circular strategies frameworks fall short in their capacity to support visioning for manufacturing. First, a circular strategies framework needs to create a comprehensive understanding of circular strategies, as relevant for the purpose (Brown et al., 2019) and context (Blomsma, 2018). Think, for instance, of the difference in the main functions of insurance and finance firms, retail and wholesale businesses, service providers, and manufacturing companies. Different circular strategies will be relevant in these contexts (Rashid et al. 2013; Johannsdottir 2014; Upadhyay et al., 2019).

Currently a multitude of frameworks exist on all levels of the landscape. See for frameworks on the macro level, for example: Allwood et al. (2011), Reike et al. (2018), Bocken et al. (2016), or Braungart and McDonough (2002). Likewise, for meso level frameworks for materials, see for water (WssTP, 2015) and biomass (ECN, 2018); or fashion and textile frameworks by EMF (2017), Inditex (2016) and Mistra Future Fashion (2018). On the micro level, consider: Gispen's (2018) framework for circular furniture, *The 10 R's of Circularity* by (Mitsubishi Electra, 2018), the Ricoh Comet Circle™ (Ricoh, 2018) (first used in 1994), or the framework used by Konecranes (2018). Likewise, on the nano level: Circular Jeans by Levi Strauss & Co. (2015), and Re-Entry for carpet tiles (Interface, 2016). Lastly, on the networked level, consider: Ehrenfeld and Gertler, 1997; Aguinaga et al., 2018; Pauli, 2010.

A notable exception of circular strategies frameworks exists on the meso level that apply to specific business types, in particular to manufacturing. One exception is the ResCom framework by Rashid et al. (2013), which targets manufacturing companies. However, this framework is also not well suited to supporting innovation processes, as it includes few circular strategies and contains a limited consideration of business processes.

In addition to creating a comprehensive understanding of circular strategies, a circular strategies framework that supports visioning needs to both map strategies currently applied as well as find opportunities for improved circularity for a range of business processes from a systemic point of view. In this aspect, current frameworks are also lacking as they are often derived or compiled to serve as a summary or overview of a piece of (mostly theoretical) work, as opposed to being purposefully developed for use in COI in and with businesses (Niero and Hauschild, 2017; Kalmykova et al., 2018; Blomsma, 2018; Sakao and Brambila, 2018). However, to establish a vision it is important to both understand the current situation - e.g. what is already being done towards CE, or what capabilities provide a basis for this, as well as to identify what opportunities are present and desirable. Current circular strategies frameworks are not designed to capture an overview of both the current situation and ideas for future innovation.

Another shortcoming of current circular strategy frameworks is that they exhibit ambiguity with regards to the meaning of and relationships between the included circular strategies, allowing the same term to adopt multiple meanings - sometimes with radically different outcomes from a resource perspective (e.g. whether recycling keeps material quality on a consistently high level, or whether it represents downcycling) - or to be rendered inapplicable to some contexts (Reike et al., 2018; Blomsma, 2018).

This paper addresses these shortcomings, by a) providing an example of a process of how a circular strategies framework can be developed for a specific business type with the ability to support COI processes, b) proposing a circular strategies framework for the manufacturing context, resulting in the Circular Strategies Scanner, with c) an accompanying set of definitions of circular strategies (including commonly used synonyms). In addition to this, we provide d) an example of how such a framework can be used to structure and guide the early phases of COI, in order to show the relevance of visioning approaches within CE transition methodology.

3. Methodology

Design Research Methodology (DRM) was applied for the development of the new circular strategies framework for manufacturing, as this method is particularly suited to the deliberate iteration of methods and tools (Blessing and Chakrabarti, 2009). Next, a high-level overview of the aim and activities in each phase is provided. See Figure 2 for an overview: more details are provided in the sections dedicated to each respective phase. The development of the proposed framework took place from November 2017 to July 2019.

Research clarification - This phase, already discussed in the previous section, served to refine the research gap and identify the need for a framework specifically for manufacturing companies.

Descriptive study I - This phase served three goals. First, a list of circular strategies to be included in the framework was compiled. Second, criteria that could be used to guide the development process of the new framework were articulated, which, third, were used to choose an existing framework as the basis for the development of the new framework. A series of workshops and meetings were held for this purpose. Iterations of the strategies list, their definitions and the framework requirements were performed throughout the project, but are presented as a single phase for clarity and brevity.

Prescriptive study I - A series of workshops and follow-up meetings were held to conceptualize and develop a first version of the circular strategies framework, as well as the corresponding clarifications and elaborations on strategies, and the relationship between them.

Descriptive Study II - In this phase the applicability and usefulness of the framework in the context of the manufacturing sector was evaluated and improvement opportunities sought. Workshops were performed with three manufacturing companies from the heavy machinery, electronics and furniture sector.

Prescriptive study II - A series of meetings was held to discuss the implementation of the improvement opportunities, based on insights from *Descriptive Study II* and the iterations of the *Research Clarification* and *Descriptive Study I* phases. A second version of the framework and a final list of strategies and their definitions were developed during this phase.

Moreover, the approach applied was deliberately transdisciplinary. That is, it aimed for establishing "a common system of axioms for a set of disciplines," which was achieved in two ways (Sakao and Brambila-Macias, 2018:1400), see also Figure 2:

(1) *Adopting a systemic view* - In the context of (more) circular manufacturing this means the alignment of the different business processes, which together contribute to the creation of circular systems. The perspectives of these processes therefore need to be included.
(2) *Inclusion of non-academic stakeholders* - Creating (more) circular manufacturing systems entails affecting changes in manufacturing companies. As such, it is important to acknowledge the perspective of manufacturing companies in the development of the new framework.

The first type of transdisciplinarity was implemented through the creation of the CIRCit research consortium[3] to represent the knowledge related to business model strategy, product design, and a range of operational processes such as sourcing, manufacturing, logistics, through-life support, digital technologies and end-of-life operations, but also sustainability aspects and value chain management.

The second type of transdisciplinarity was implemented through application of the framework on retrospective company cases, as well as applying the framework in ongoing research that is actively supporting companies in implementing circular practices. Furthermore, the consortium contained representatives of the interests of manufacturing companies, such as industry associations. Through this, the perspective of 'real-world' considerations was added. Next, the outcomes of each phase is presented.

[3] See for more information about the consortium: www.circitnord.com.

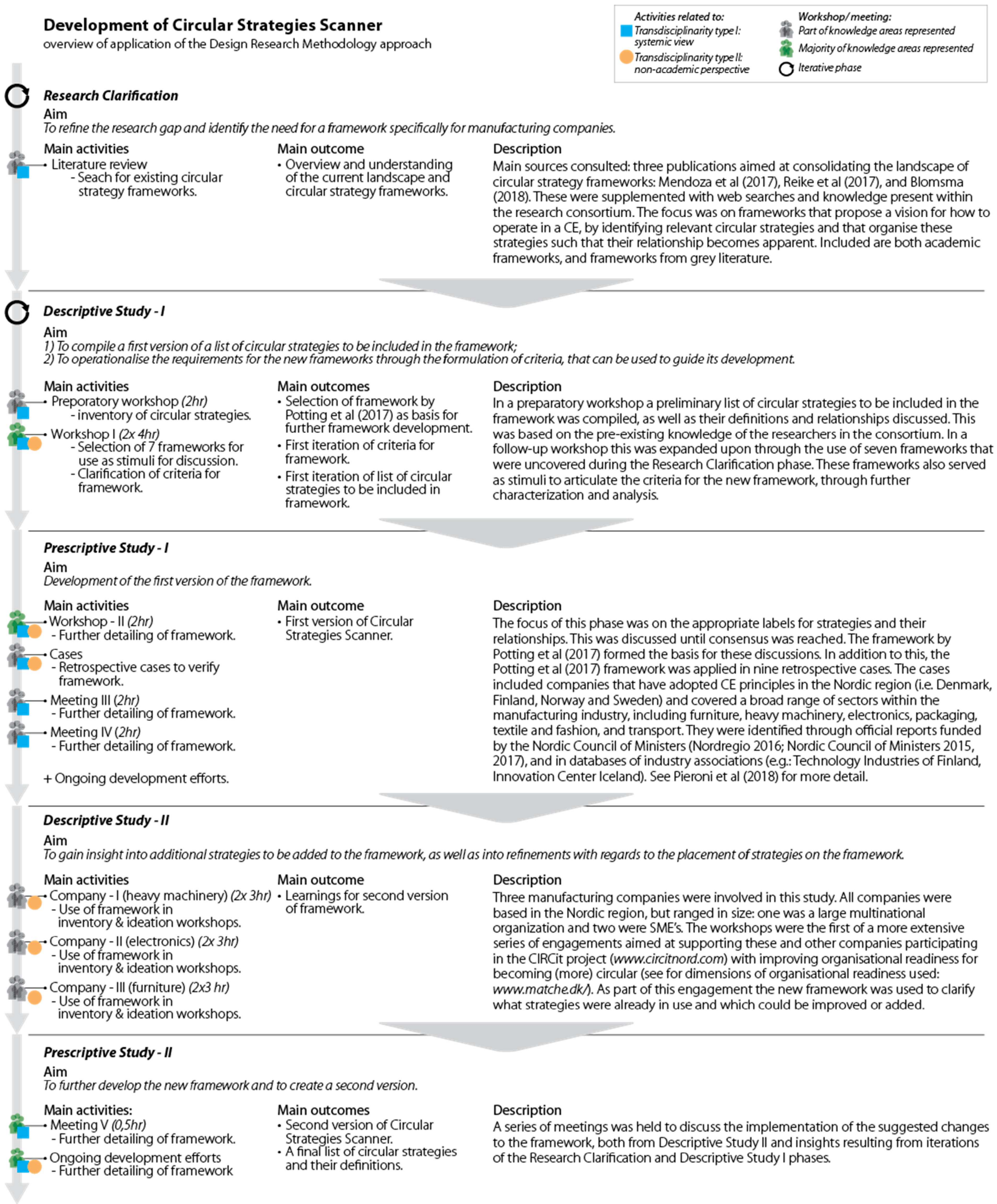


Figure 2. Schematic illustration of the approach followed for the development of the Circular Strategies Scanner.

4. Descriptive Study I - criteria for a circular strategies framework for manufacturing companies

This phase served to establish a foundation for the development of the new framework. This was done in the following manner, see also Figure 2.

4.1. Rationale behind Descriptive Study I

Due to the lack of suitable meso level frameworks with a business type orientation, macro frameworks were used as a starting point with the aim to adapt their generic applicability and generative capacity for manufacturing companies. From the macro frameworks 1) relevant circular strategies were extracted, and 2) criteria that could be used to guide the development process of the new framework were articulated, which 3) were used to choose the best fitting existing framework as the basis for the development of the new framework. In particular, seven macro level frameworks uncovered during the Research Clarification phase were used: Thierry et al. (1995), Parkinson and Thompson (2003), Allwood et al. (2011), Bocken et al. (2016), Nussholz (2017), Potting et al. (2017), and Blomsma (2018). These were included based on 1) their range of relevant strategies for the manufacturing context, 2) their inclusion of definitions and/or examples of these strategies and 3) representing a broad range of approaches to classify or organise the strategies in relation to each other. This served to have contrasting definitions and approaches that could be discussed and analysed.

4.2. Outcomes Descriptive Study I

The final version of the list of included strategies, their definitions and examples, which continued to be iterated throughout the development of the framework, can be found in Table 2 (see section 7. *Prescriptive study II*). Here, the focus is on the five criteria for the new framework that were developed to detail the main functions of a circular strategies framework (create understanding of CE, map current CE initiatives, generate ideas for increased circularity). The criteria were iterated until they represented five clear requirements for the development of the new framework. This section concludes with the selection of the best fitting existing framework.

Criterion #01: A tool for inspiring, motivating and aligning people

In innovation processes it is important to invoke relevant frames, acknowledge cognitive principles (which involve cognitive limits, but also principles of attention, inspiration and motivation) and, in collaborative settings, to consider the alignment of understanding, mindsets and interests between different stakeholders. Language, both visual and written, plays an important role in this: it helps directing attention, summarising and synthesising information from internal and external knowledge sources and it supports orientation towards relevant aspects of the context (Biloslavo et al., 2018; Breuer et al., 2018) and in the creation of a shared vision, also in the context of CE (Blomsma, 2018). Therefore, in line with the frameworks discussed above, the proposed framework should 01) represent a complex phenomenon in an easily accessible manner in order to inspire, motivate and align people.

Criterion #02: A tool for describing current situations and identifying opportunities, both incremental & transformative

A framework suitable for use by a wide variety of manufacturing businesses, cannot be broad in the sense of the frameworks on the macro level, as it will lose relevance. At the same time, it can also not be specific in the sense of the company and product frameworks, as this would mean it is limited in its reach and impact. However, the new framework should be suitable for describing both current initiatives and have the capacity to systematically explore relevant strategies and identify new opportunities. As such, the new framework should balance the strengths of the macro and meso level frameworks - which are generative and allow for the exploration of alternatives, with that of the micro and nano level frameworks - which offer greater specificity in relation to the context in which strategies are applied. Thus, the new framework should: 02a) balance the generation of new ideas, with that of describing existing situations. This indicates that it is preferable to include a diverse set of circular strategies, as opposed to high-level aggregated groups of strategies.

Furthermore, opportunity finding needs to point to the potential for improving existing strategies, as well as to radically different ways of achieving goals and creating, delivering and capturing value. This can involve the design, production and/ or transport of physical products, but it can also require a change in the business logic and operations that changes how products are commercialized and consumed. Think of the implementation of access-over-ownership models, or radical dematerialisation through a change in paradigm. As such, the framework should 02b) provide an overview of the spectrum of available strategies ranging from incremental to transformative. This indicates that the set of included strategies should cover strategic as well as operational business processes.

Criterion #03: A tool for facilitating alignment of changes in business processes and capabilities
Circular strategies frameworks aimed at specific business types need to provide insight into which business processes relevant for that business type need to be aligned. This means, following Allwood et al. (2011), Potting et al. (2017) and Reike et al. (2018), that the new framework should indicate which circular strategies may apply to which flows. In the manufacturing context, this implies 03) indicating which strategies affect which business processes and related capabilities.

Criterion #04: A tool for bringing together efficiency and effectiveness strategies, and strategy configurations
Following e.g. Pauli (2010), Stahel (2006), Potting et al. (2017), Reike et al. (2018) and EMF (2015), we adopt the view that both resource-efficiency and resource-effectiveness are important in the manufacturing context. The new framework therefore should: 04a) explicitly include the reduction and avoidance of resource use and impacts, as well as resource productivity strategies aimed at continued use and value delivery.

Moreover, many manufacturing companies operate in complex scenarios, that can be thought of as circular configurations: situations where two or more circular strategies are present (Blomsma and Brennan 2017, Blomsma 2018). Think of product/ service systems where direct reuse, but also repair, refurbishment and remanufacturing are taking place, in addition to the recycling of materials. As such, the proposed framework should: 04b) allow for generating insight into circular configurations.

Criterion #05: A tool for alignment with drivers: value creation & capture orientation
Businesses need to create and capture value to continue their activities. It is widely acknowledged that circular strategies have the capacity to contribute to this. However, not many current frameworks support the identification of the type of value that can be captured through which strategies. The new framework therefore needs to be aligned with the perspective of systemic value creation and capture. Support in identifying this can enable assessing and measuring outcomes and tracking potential deviations from the planned future state, which is fundamental to transition management (Breuer et al., 2018). As such, the proposed framework: 05) has to point to the value drivers that circular strategies can contribute to. That is: the framework has to help users identify relevant contributions to value creation and capture, such as improved efficiencies, supporting optimal use during the use phase, and value recovery opportunities, resulting in either financial or non-financial gains within or outside the company (Circle Economy et al., 2016). As these may be relevant for business shareholders, but also suppliers and customers, the environment and society they need to be formulated such that relevance for these stakeholders can be easily appreciated.

Next, the seven frameworks were compared and rated on these criteria, see Table 1. Although none have a perfect score, the framework by Potting et al. (2017) scores the highest: it represents a complex phenomenon in an easily accessible manner (criterion 01), contains a comprehensive set of circular strategies (criterion 02b), includes efficiency as well as effectiveness strategies (criterion 04a) and points to value drivers that circular strategies can contribute to (criterion 05). This framework was therefore chosen as a basis for further development of the new framework, with its relevance for different business processes and capabilities (criterion 03) identified as in need of further improvement.

Criteria The new framework should:	Bocken et al (2016)	Allwood et al (2011)	Parkinson & Thompson (2003)	Thierry et al (1995)	Potting et al (2017)	Nussholz (2017)	Blomsma (2018)
01) A tool for inspiring, motivating and aligning people.	+	++	0	++	++	+	+
02a) Balance the generation of new ideas, with that of describing existing situation.	0	+	0	+	++	+	0
02b) Provide an overview of the spectrum of available strategies ranging from incremental to transformative.	+	+	0	+	++	++	0
03) Indicate which strategies affect which business processes.	0	+	0	+	+	0	0
04a) Explicitly include the reduction and avoidance of resource use and impacts, as well as resource productivity strategies aimed at continued use and value delivery.	+	+	0	0	++	++	0
04b) Allow for generating insight into circular configurations.	+	++	0	++	++	+	+
05) Has to point to the value drivers that circular strategies can contribute to.	++	0	0	+	++	+	++
+++ = framework satisfies criterion very strongly, ++ = framework satisfies criterion strongly, + = framework satisfies criterion moderately, 0 = framework doesn't meet criterion or only marginally.							

Table 1 - Comparison of the seven frameworks that were used in Descriptive Study I using the development criteria.

5. Prescriptive Study I

During this phase the first version of the new framework was developed, through adding detail to Potting et al. (2017) as relevant for the manufacturing business type, guided by the criteria established in the above and the exploratory case studies (see Pieroni et al., 2018). The focus was on the appropriate labels for strategies, and how to convey the relationship between the included strategies.

5.1. Outcomes Prescriptive Study I

The outcomes of this phase is discussed in terms of the adaptations of the Potting et al. (2017) framework that were made. Only the major adaptations are elaborated upon: see for the first version of the framework Figure 3 and the complete set of changes Appendix A. See for definitions and examples of individual strategies Table 2 (section *7. Prescriptive study II*).

Major adaptations #01 and #02: Organisation of circular strategies according to business processes, and greater specificity for 'Reduce'

The preliminary list of circular strategies from the previous phase was organised according to the business processes as typically found in the manufacturing context, to meet criterion #03. For this, the process of transformation of raw materials into finished or intermediate goods was divided as follows. First, two areas that are related to the corporate strategy were identified: the first is changing the paradigm of practices and was named 'Replace,' and the second is a reconsideration of how value is delivered, entitled 'Rethink.' The former strategy enables radical dematerialisation through different ways of performing functions (e.g. functional replacement or new practices), which can be enabled by new technologies. This strategy was renamed from Potting and colleagues' 'Refuse' (see Medium adaptation 1 in Appendix A). The latter strategy involves new business models that are more resource efficient, such as access-over-ownership offerings, enabled by commercial models based on leasing, renting or pay-as-you-go. As such, 'Replace' concerns the

delivery of functionality through radically different means, whilst 'Rethink' delivers similar functionality through different customer relationships and which may involve a redefinition of the functional unit.

The remainder of the framework concerns operational processes. Potting et al's (2017) 'Reduce' was further divided to make its application to the following operational processes explicit: 'Raw materials and sourcing,' 'Manufacturing and logistics' and 'Product use/ operation.' This indicates that in these phases, the focus is on efficient use of resources and the reduction of harmful impacts.

The next two operational process areas respectively contain various end-of-use and end-of-life strategies. The first contains the strategies 'Upgrade' (see Minor adaptation 2), 'Repair & Maintenance' (see Minor adaptation 4), 'Reuse,' 'Refurbish,' 'Remanufacture,' and 'Repurpose'; and the second which contains the strategies 'Recycle' and 'Recover' (see Minor adaptation 1).

Major adaptation #03: Addition of the relationship between business processes
To capture the different relationships between the strategies (criterion 04b), a visual structure consisting of three levels has been created: the first occupied by 'Replace,' the second by 'Rethink' and the third by the remaining strategies. This is indicated by the relative placement of the boxes containing the strategies and the addition of arrows. This signals that, within the manufacturing context, some relationships between circular strategies are of a hierarchical nature, and some exist in the form of trade-offs and synergies. An example of a hierarchical relationship: 'Replace' may preclude the use of certain other circular strategies, when, for instance, a physical product is replaced by a virtual service. On the other hand, the application of 'Rethink' can require the support of repair and maintenance strategies to be viable, such as in certain product/service system offerings. As such, the application of either 'Replace' or 'Rethink' requires that the relevance of all strategies on the levels 'below' should be evaluated, as their relevance may change when these strategies are applied.

Circular Strategies Scanner - v1.0

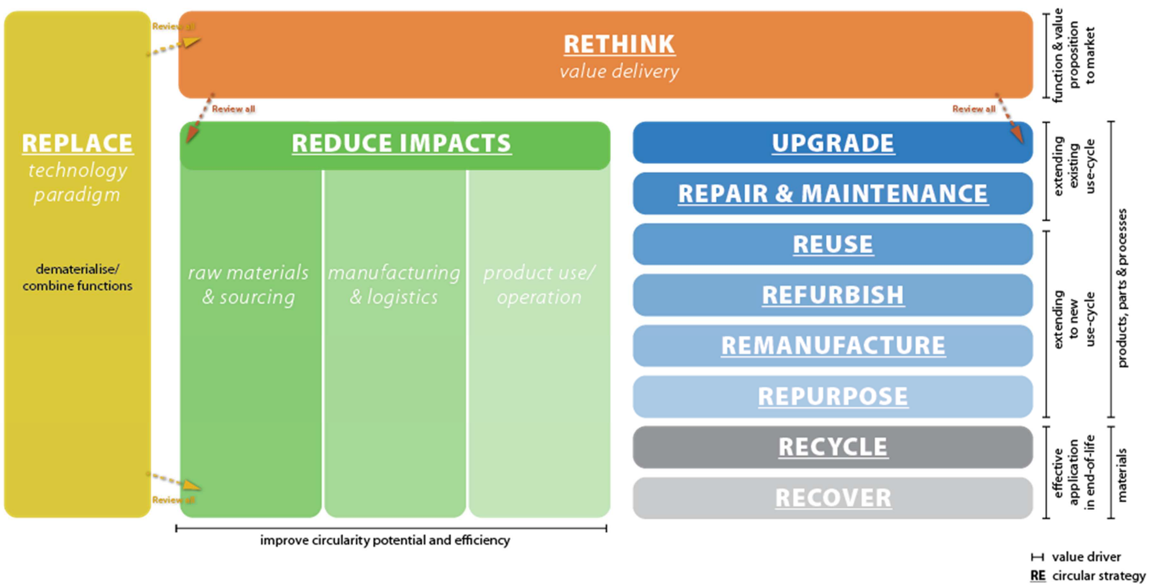


Figure 3 - The first version of the Circular Strategies Scanner.

Examples of other relationships include trade-offs: the choice, for instance, for certain durable materials such as composites may impede recycling. In this case, a strategy that facilitates product longevity, conflicts with recycling the material at the end-of-life. On the other hand, certain interventions may cause cumulative or

reinforcing effects, such as choosing a renewable material that at the end-of-life can be safely composted, allowing this single intervention to cover two circular strategies synergistically; the sourcing of materials that can be renewed and the 'recovery' of nutrients at the end-of-life. For this reason, the strategies that reduce impacts and that affect end-of-use/ life are placed on the same 'level.' When considering these strategies, therefore, it should be examined if trade-offs and/ or synergies with other strategies on this level exist.

With this structure the new framework departs from the hierarchy that Potting and colleagues use. However, the value drivers have been preserved and further refined, in line with the different business processes (see Medium adaptations 2 and 3).

6. Descriptive Study II

In this phase the framework was tested in workshops within three manufacturing businesses from the heavy machinery, electronics and furniture sectors. The aim was to gain insight into additional strategies to be added, as well as into refinements with regards to the placement of strategies. Moreover, this section provides an example with regards to how a circular strategies framework can be used in the early stage of COI.

6.1. Use of the new framework in workshops in Descriptive Study II

With each business a two-part workshop was carried out. The first part mapped the circular strategies currently applied within a product or service (category). Participants were asked to prepare by classifying their offering (products, services or PSS), and to identify and describe the strategies currently applied. In the workshop, all strategies were mapped onto the Scanner and discussed: the current implementation level of the strategies, as well as their respective affinities to the business and their resource efficiency impact (e.g.: percentage of total sales or revenues, percentage of sold products recovered for end-of-use/life treatment). The second part of the workshop focused on scanning for new opportunities to enhance or append additional strategies, through the evaluation of the current state and the identification of gaps and improvement hot spots. Case examples of other companies employing strategies across the full range of strategies covered by the Scanner were used to stimulate the discussion with participants.

In total, each workshop lasted approximately six hours and involved participants with diverse skills and expertise, such as marketing and sales, services and product development, after sales and customer services, operations, corporate social responsibility, IT, business strategy and finance. Moreover, representatives from the business leadership or top management participated in all workshops. The number of participants varied from three to ten, according to the business size.

6.2. Outcomes Descriptive Study II

An example of the mappings created in both phases of the workshop can be found in Figure 4. The top part represents individual initiatives currently applied by one of the companies (one initiative per number). This represents current CE initiatives or current capabilities that can contribute towards increased circularity. The bottom represents improvement areas: circular strategies that could be improved or scaled up, or strategies that could feasibly be added. Comparing the current state with new opportunities, it can be seen that ideas were generated that increased the coverage of circular strategies, some even developing into more advanced concepts when synergies between circular strategies were identified.

During the workshops with the companies, the framework functioned as a boundary object (Star and Griesemer, 1989) for different participants to align their perceptions. That is: clarifying the current state together allowed participants to build a common picture of their organisations' ongoing CE initiatives and current capabilities, and to align their understanding of their nature and maturity. Moreover, the shared

exploration of new opportunities helped the participants to share their perceptions of these opportunities, and set priorities for their innovation pipeline. In all cases the visioning exercise helped to identify why and where to focus, whether in relation to the development of circular business models, applying circular product design principles, the application of smart technologies, the assessment of potential initiatives in relation to their sustainability impact and/ or areas where collaboration with other stakeholders needed to be sought[4]. As such, this visioning exercise facilitated with the Scanner served to guide and direct the COI process to relevant initiatives and appropriately set the scope for these efforts early on. Direct feedback provided by individual participants supports this. Representative responses were “quite helpful”, “great tools” and “visualization with the boards helped the conversation a lot.”

However, observations were made that were used to improve the framework further. First, it was noted that efficient logistics is relevant throughout a product’s life, and not just before, during and after manufacturing. That is: for operations extending existing life cycles or those that extend the product life to new use-cycles and in recovering materials for end-of-life treatment, logistics must be cost- and carbon efficient. It should be placed in such a way to indicate this broader relevance.

Moreover, it was observed that it is also possible to use the sourcing stage as an opportunity to recapture waste that has already entered the environment. The various projects around recovering plastic from the oceans are examples of this (The Ocean Cleanup 2018, Plastic Oceans 2018), and the framework should also highlight the possibility of sourcing such materials. These observations led to the Medium adaptations 1 and 2 discussed in the next section, see also Appendix C.

[4] For more on this, see the CIRCit website (circitnord.com).

Mapping of current and possible company strategies using Circular Strategies Scanner v1.0

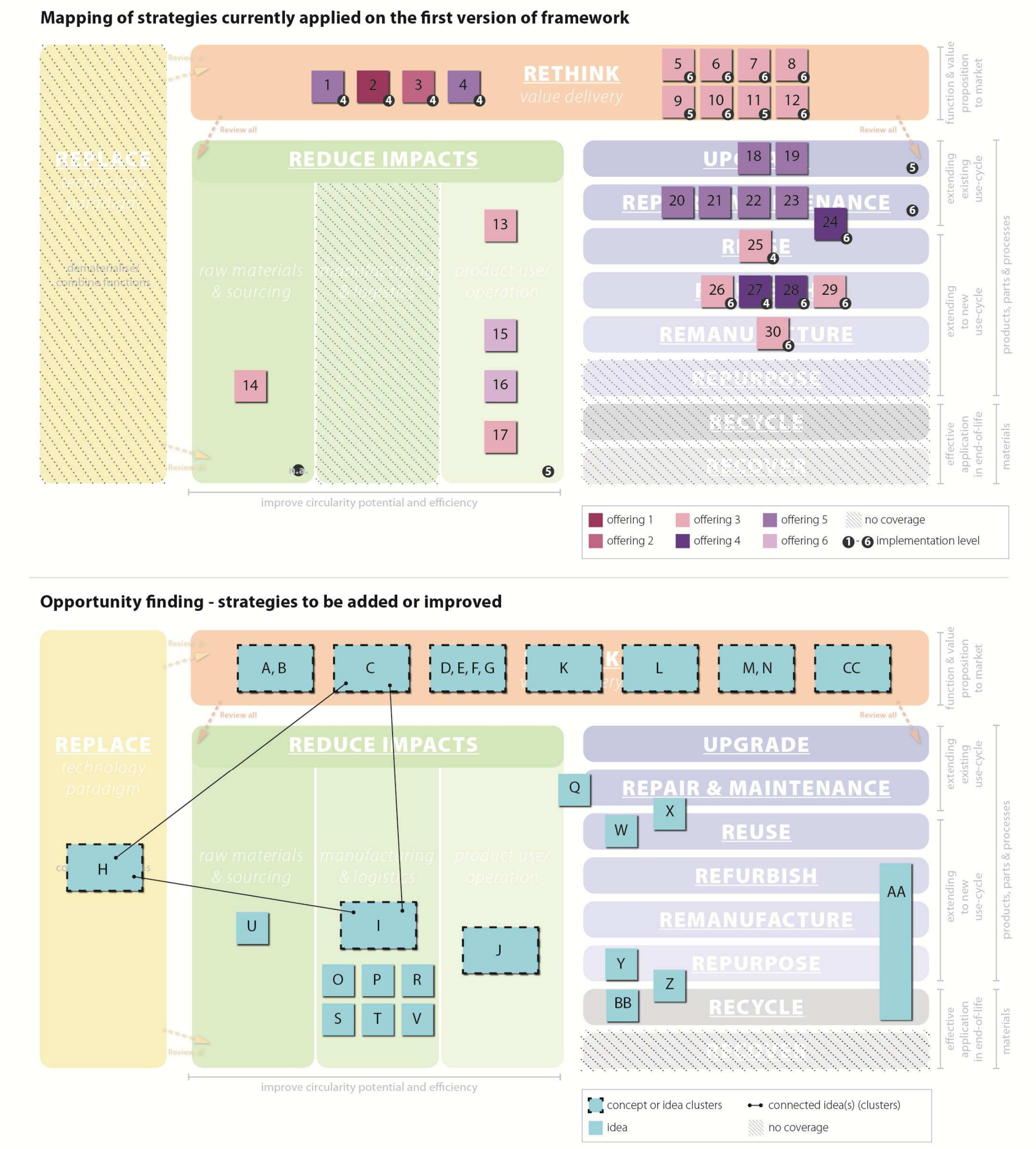


Figure 4 - Example of how the first version of the Circular Strategies Scanner was used in a two-part workshop with one of the companies participating in the CIRCit project. One or double letters are used per strategy: connected or grouped ideas represent closely related ideas that together constitute a new concept. Results are anonymised for reasons of confidentiality.

7. Prescriptive study II

The aim of this phase was to develop a second version of the framework on the basis of the identified improvement opportunities. The main activities were ongoing development efforts, supplemented by a series of meetings held to discuss the implementation of the suggested changes stemming from *Descriptive Study II* and the continued iteration of the *Research Clarification* and *Descriptive Study I.*

7.1. Outcomes Prescriptive Study II

No major adaptations were made, therefore the focus here is on medium adaptations: see for the second version of the framework Figure 5 and the complete set of changes Appendix B. See for definitions of individual strategies Table 2.

'Logistics' was assigned a separate layer such that it encompasses all the operational process areas. In addition to this and in a response to additional sources considered, 'Energy' was added as a layer encompassing all circular strategies (Cullen, 2017; Mestre and Cooper, 2017). That is: circular strategies should be considered with the intent to reduce overall energy consumption, and the use of clean(er) and renewable sources wherever possible.

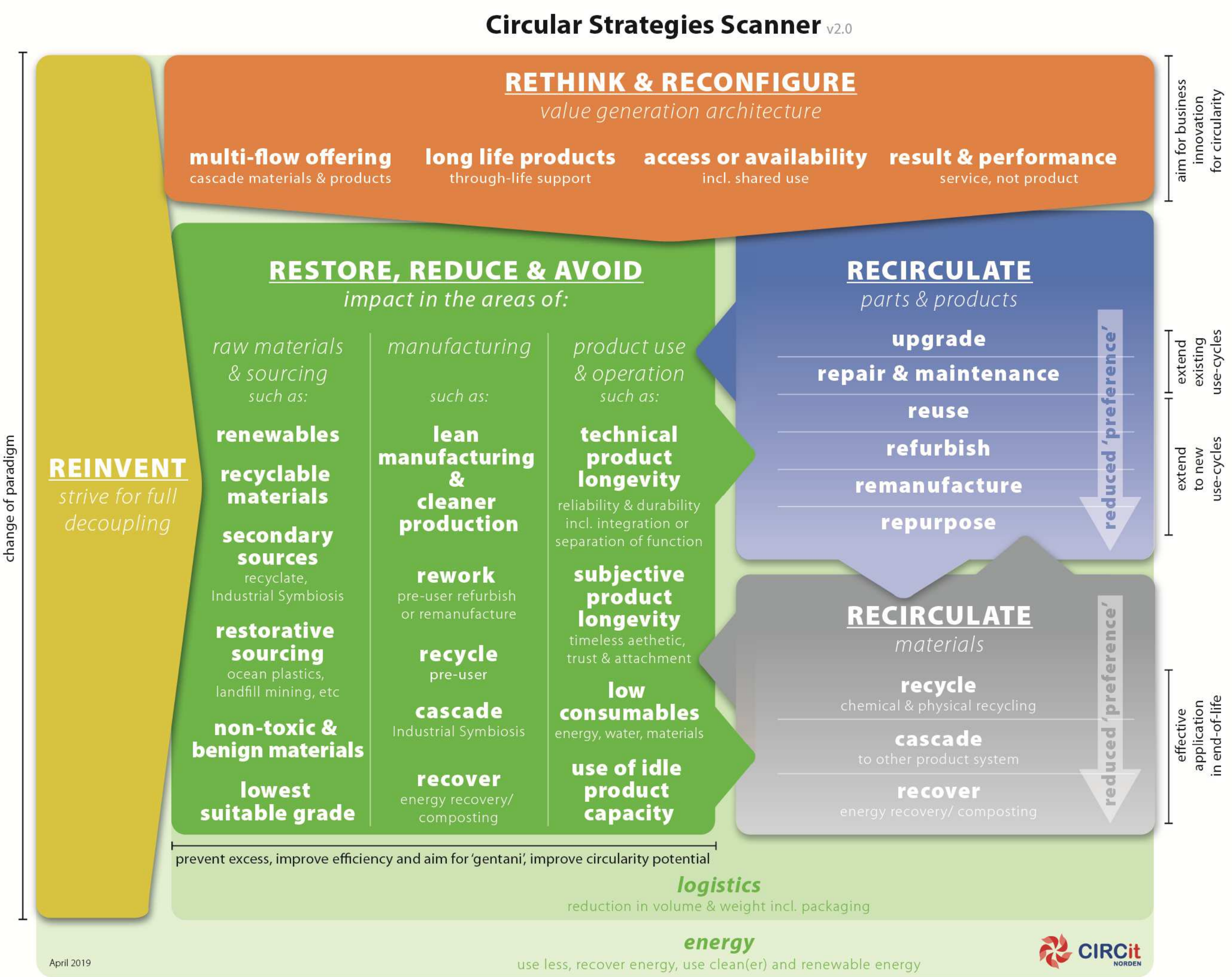


Figure 5 - The second version of the Circular Strategies Scanner.

Moreover, the heading 'Reduce impacts' was changed to 'Restore, reduce & avoid' to more fully reflect the range of strategies relevant for raw materials and sourcing, manufacturing, and product use and operation.

Also, more detail was added to the visual representation of the framework, which entailed the addition of suggested strategies in this area (see Minor adaptation 2). These strategies are meant to be inspirational, rather than exhaustive. In some cases this resulted in allocating strategies to multiple places in the framework, which is in line with Potting et al. (2017) and Reike et al. (2018). Recycling, for instance, can be found in both the category Restore, Reduce and Avoid, as well as in the category Recirculate - Materials. This reflects the fact that pre- and post consumer recycling can take place. Similarly, cascading, or industrial symbiosis can take a variety of different forms: as a sourcing strategy, as a way of valorise manufacturing waste, but also as an end-of-life strategy for materials. These multiple occurrences are also due to departing from the hierarchical structure used by Potting et al. (2017) (see also section *5. Prescriptive Study I*). For clarity descriptors have been added to signal the specific application of a strategy (see Minor adaptation 3).

Similarly, detail was added to the Rethink & Reconfigure category to clarify the framework's relationship with business models aspects. Two sources were consulted for this: Bocken et al. (2016) and Tukker (2004), chosen because of their seminal importance in the CE field (Pieroni et al. 2019) These respective typologies were synthesised into four main categories that cover circular business model strategies available to manufacturers and that represent a fundamental change to the logic of how such a business operates: 'Multi-flow offering,' 'Long-life products,' 'Access or availability,' and 'Result and performance.' This, as opposed to including strategies that are more appropriately thought of as supporting operational strategies such as efficiency and encouraging sufficiency.

Strategies included in the Circular Strategies Scanner (further developed from Potting et al. 2017)		
Driver	**Strategy** Synonyms	**Area of application or sub category** **Recirculation strategy** & synonyms ***Definition*** *(specifics)* • **Example practice(s)/ specifics**
Enable smarter business concepts through striving for full decoupling.	**Reinvent** Refuse	**The paradigm** *Make physical products redundant by offering the same function or combined functions, usually enabled by radically different product, technology or both (Potting et al. 2017).* • The 'bring-your-own' movement facilitates replacing such single use items such as coffee cups. • Music and video streaming services negate the need for data carriers such as CDs and DVDs. • Multi-functional devices such as smart phones combine the functionality of multiple devices (camera, GPS, phone, calculator, alarm clock, sound system, computer) in a single device.
Enable smarter business concepts through business model innovation for circularity. Products tend to not radically change, although the technology can evolve.	**Rethink & reconfigure** Revolution Replace	**Business models**
		Multi-flow offering – cascade materials, parts & products *Extend the life of materials or products in a manner that exploits their residual value and becomes a significant part of the offering of the business. May involve providing new forms of value (Bocken et al., 2016).* • Leesmap (magazine subscription where the price decreases with the age of the magazines). • British Sugar (from the core-business of sugar, to also selling many different co-products).
		Long life products – through- life support *Extend the life of products through offering support during their lifetime (Tukker, 2004).* • Provision of maintenance, offering of repair services, or sales of spare parts.
		Access or availability – incl. shared use *Satisfying user needs without transferring ownership of physical products. Instead, user or consumer pays for access to the product for a certain period of time (Tukker, 2004).* • Bike or car sharing services (e.g. Bycyklen in Copenhagen, Santander Cycles in London, and many other cities around the world; Drive Now, Green Mobility, Zipcar, Blablacar). • Clothing rental and subscriptions (e.g. Rent the Runway, Vigga, Mud Jeans).
		Result & performance – service, not product *The provider of the service delivers an outcome for the customer (Tukker, 2004).* • Performance contracts (Rolls Royce - Power by the Hour).
Prevent excess, improve efficiency and aim for 'gentani', improve circularity potential.	**Restore, reduce & avoid**	**Raw materials & sourcing** *Improve circularity potential and efficiency in the sourcing process (Mestre and Cooper, 2017).* • Sourcing of renewables. • Sourcing of recyclable materials. • Secondary sources (recycled materials, Industrial Symbiosis, other cascades). • Restorative sourcing (Use former 'wastes' as input: Landfill re-mining or using ocean plastics). • Use of non-toxic or benign materials (to facilitate re-absorption in natural cycles). • Use the lowest suitable grade of materials suitable (Reserve the highest-quality resources for the most demanding task, and use used resources further down the chain).
		Manufacturing *Improve circularity potential and process efficiency in product manufacture through consuming fewer natural resources or energy, aim for 'gentani' (the absolute minimum input required to run a process) (Potting et al., 2017).* • Lean manufacturing & cleaner production (use less energy and materials, treat wastes, etc). • Rework (pre-user refurbishment or remanufacture). • Recycle (pre-user recycling). • Cascade (find uses for manufacturing waste: internally/ at other facilities (Industrial Symbiosis)). • Recover (energy recovery, or recovery of biological nutrients).
		Product use & operation *Improve circularity potential and efficiency in product use and operation through wiser use and operation of products (usually enabled by digital technologies), and aim for 'gentani' (the absolute minimum input required to run a process) (Potting et al., 2017; Reike et al., 2018).* • Enable product longevity through high product integrity and robustness. • Use idle product capacity (historical usage data can be used for improvements such as better scheduling (of downtime), and (give insight into the possibilities for) pooled or shared use). • Low consumables of energy, water and materials during product use and operation.
		Logistics *Improve process efficiency in logistics operations, aim for 'gentani' (minimum input into a process (Greenbiz, 2014)* • Combine forward & return logistics. • Incentivize eco-friendly driving and transport. • Minimize, reuse or recycle (transit) packaging.
		Energy

		Improve energy efficiency and use clean(er) sources of energy (Cullen, 2017; Mestre and Cooper, 2017).
		• Use less energy • Renewable energy

<u>Strategies included in the Circular Strategies Scanner</u> *(cont).*		
Driver	**Strategy**	**Area of application or sub category** **<u>Recirculation strategy</u>** & synonyms ***Definition*** *(specifics)* • **Example practice(s)/ specifics**
Extend existing use cycles with the purpose of capturing (residual) value or to reduce value loss from continued use of parts and products	**Recirculate**	**Parts & products**
		<u>Upgrade</u> – Update, modernize, renew, retrofit, rebuild, overhaul, revive.
		Extend existing use cycle by adding value or enhancing the function of a product in respect to previous versions (Parkinson and Thompson, 2003; Potting et al., 2017).
		• Aesthetic upgrades (i.e. changing the coat or sleeve of a product due to a new preference). • Functional upgrades (i.e. software upgrades, hardware upgrades).
		<u>Repair & maintenance</u> – Corrective, condition based, predictive and prescriptive maintenance
		Extend existing use cycle by countering wear and tear, and correcting faulty components of a defective product/part to return it to its original functionality. ((Partial) disassembly envisioned, limited warranty may be issued). (Thierry et al, 1995; Stahel, 2006).
		• Providing a product with a service, which may involve the lubrication of critical parts, checking fasteners, the tension of chains and cables, the replacement of worn-out parts, etc. • Repair may involve the restoration or replacement of faulty parts and components.
Extend to new use cycles with the purpose of capturing (residual) value or to reduce value loss from continued use of parts and products.		<u>Reuse</u> – As-is reuse, redistribution, product cascading, minimise.
		Extend to new use cycle by reusing a part/ product (discarded/ not in use) that is still in good condition and can fulfil its original function in a different use context (new customer/user). (May involve a minimum amount of condition monitoring such as cleaning or repackaging. No warranties are provided and no disassembly is involved.) (Saavedra et al., 2013)
		• Selling used goods on platforms such as E-bay, • Return and resale of second hand goods through stores, such as Patagonia and Bergans. • The xStorage Home system (by Nissan and Eaton) gives old lithium-ion batteries from Nissan Leaf a second life inside of homes and businesses as backup and solar storage batteries.
		<u>Refurbish</u> – Recondition, retrofit, refresh, remodel.
		Extend to new use cycles by returning a part/ product (discarded/ not in use) to a satisfactory working condition that may be inferior to the original specification. (This may involve: cleaning, repairing, resurfacing, repainting, re-sleeving. Partial disassembly envisioned. In the case of traditional product sales, a warranty for all major parts may be issued (less than the newly manufactured equivalent)). (Ijomah, 2002, 2009; Saavedra et al., 2013).*
		• For example: taking in relatively modern, but disused white goods and performing repairs and/ or replacing lost parts and finding new users for the refurbished products (e.g. Norsk Omburk).
		<u>Remanufacture</u> – Rebuild, overhaul, remake.
		Extend to new use cycles by returning a product (discarded/ not in use) to at least Original Equipment Manufacturer (OEM) performance specification and quality. (Usually more rigorous and costly than refurbishment and involves total disassembly and reassembly. In the case of traditional product sales, a warranty that is at least equal to that of a newly manufactured equivalent may be issued). (Ijomah, 2002, 2009; Saavedra et al., 2013).
		• Renault engine blocks
		<u>Repurpose</u> – Alternate use.
		Extend to new use cycles by using a product (discarded/not in use) or its parts for different functions (Potting et al., 2017; Reike et al., 2018).
		• Mærsk providing containers to fit housing purposes in Copenhagen Village. • Using product packaging as storage or glassware (Nutella, Douwe Egberts).
Effective application in end-of-life of materials with the purpose of capturing (residual) value or to reduce value loss from continued use of materials.	**Recirculate**	**Materials**
		<u>Recycle</u>
		Extend material lifespan by processing them in order to obtain the same or comparable quality (Allwood et al., 2011).
		• Can-to-can recycling in beverage cans. • Chemical recycling of nylon.
		<u>Cascade</u> – Downcycling, upcycling.
		A subsequent use that significantly transforms the chemical or physical nature of the material (Sirkin and Ten Houten, 1994).
		• Repurposing of used clothing as an insulation material. • Used coffee grounds from coffee shops processed into biofuel, as medium for cultivation of edible mushrooms, for use in beauty products, etc.
		<u>Recover</u>
		Recover energy or nutrients from composting or processing materials. (Reike et al., 2018).
		• Incineration, pyrolysis or anaerobic digestion (recovery of energy). • Composting (recovery of biological nutrients).

Table 2 - Overview of the definitions of the circular strategies as used in the Circular Strategies Scanner.

8. Discussion

The Circular Strategies Scanner illustrates how to support visioning in COI processes, through supporting the explication of CE, mapping current CE initiatives, and generating ideas for increased circularity. With this, the framework of Potting et al. (2017) was significantly improved upon for the manufacturing context, see Table 3.

Criteria **The new framework should:**	**Potting et al. (2017)**	**Circular Strategies Scanner - v2.0**	**Summary of improvements that were realised**
01) A tool for inspiring, motivating and aligning people.	++	+++	*Improved capacity to serve as a boundary object where stakeholders can clearly identify their (influence on) activities, and see the applicability and relevance of circular strategies (see also the criteria below).*
02a) Balance the generation of new ideas, with that of describing existing situation.	++	+++	*The Scanner can directly and without transformations be used as a tool for mapping the circular strategies that are present in a situation, as well as for exploring what strategies can be improved or added (see section 6).*
02b) Provide an overview of the spectrum of available strategies ranging from incremental to transformative.	++	+++	*The Scanner groups circular strategies according to their potential for change in circularity levels. Strategies that can be thought of as having potential for incremental change are grouped under* Restore, reduce & avoid*; strategies that aim for higher levels of circularity through business model innovation are grouped in* Rethink & reconfigure*; and strategies that radically transform both business and user practices and achieve radical decoupling are placed in* Reinvent.
03) Indicate which strategies affect which business processes and related capabilities.	+	++	*The circular strategies in the Scanner are organised according to the business processes they apply to.* Reinvent *and* Rethink & reconfigure *represent groups that affect business strategy, and the remaining groups respectively affect operational processes, ranging from raw materials and sourcing, manufacturing, product use and operation, to the recirculation of parts and products, and materials.*
04a) Explicitly include the reduction and avoidance of resource use and impacts, as well as resource productivity strategies aimed at continued use and value delivery.	++	+++	*The Scanner covers a wider range of circular strategies, giving a more comprehensive overview of circular strategies that aim for the reduction and avoidance of resource use and impacts, as well as those that improve resource productivity strategies.*
04b) Allow for generating insight into circular configurations.	++	+++	*The Scanner implements a means of systematically exploring connections between circular strategies, through organising them in three 'levels' that indicate their relationship. This relationship can be bi-directional: e.g. a change in circular strategies in* Restore, reduce & avoid *may impact the circular strategies in* Recirculate and vice-versa*; or it may may be a unidirectional relationship where a change in* Reinvent *requires the reexamination of the relevance of circular strategies in* Rethink & reconfigure, *or where a change in* Rethink & reconfigure *requires a reconsideration of the strategies applied in* Restore, reduce & avoid.
05) Has to point to the value drivers that circular strategies can contribute to.	++	+++	*Each group of circular strategies in the Scanner is clearly linked to a value driver that aids its users in identifying relevant contributions to value creation and capture, such as improved efficiencies, supporting optimal use during the use phase, and value recovery opportunities, pointing to opportunities for either financial or non-financial gains within or outside the company.*
+++ = framework satisfies criterion very strongly, ++ = framework satisfies criterion strongly, + = framework satisfies criterion moderately, 0 = framework doesn't meet criterion or only marginally.			

Table 3 - Overview of the the improvements that the new framework makes in relation to the framework by Potting et al. (2017) that was used as a basis for its development.

A strength of using the Scanner in COI is that it provides a way of systematically exploring circular strategies. It thus provides guidance in identifying what business areas eco-innovation for CE is possible or necessary. For instance, when improved recycling is identified as an opportunity, the Scanner indicates that other circular strategies in the operational areas of raw materials and sourcing, manufacturing, product use and operation, and the recirculation of parts and products may be affected. Such impacts may be synergistic and result in increased overall circularity (e.g. the choice to change to a recyclable material to enable end-of-life recycling also enables recycling of waste within the manufacturing process), or they may take the form of trade-offs and require additional management or development for resolving them (e.g. changing to a recyclable material negatively affects the technical longevity of a product). Further work could focus on providing additional guidance with regards to how to systematically identify synergies and trade-offs.

Application of the Scanner furthermore strengthens the connection between eco-innovation and CE, by linking it with transformative innovation (De Jesus et al. 2018). It does this in two ways in COI processes. First, due to possibilities uncovered in the operational area, it can trigger a re-evaluation of the value generation architecture. Second, when the value generation architecture is the starting point, the Scanner indicates that the role of the circular strategies on the operational level need to be revisited as their relevance may increase or diminish depending on the context. In both cases, the Scanner invites a reconsideration of the system the manufacturing company is attempting to transform and links circular strategies together in circular configurations: situations where two or more circular strategies work together (Blomsma et al., 2018).

The range of sectors used for the validation efforts - heavy machinery, electronics and furniture - points to the broad applicability of the Scanner for manufacturing companies from different sectors. However, the framework could be further strengthened by validation with a wider set of manufacturing companies, including those that (also) operate within the biocycle, or that provide dissipative products (e.g. paints, lubricants, cleaning agents and other chemicals).

Further work should address how the Scanner can be linked to the assessment of (combinations of) circular strategies and different implementation scenarios, such that in the early stages of innovation processes the impact on economic, environmental and social systems can be evaluated and actions implemented to minimise negative impact and maximise positive impact. It could furthermore be explored whether the framework has potential to address the lack of a common understanding between value chain actors, which is perceived as an obstacle for the implementation of CE (Machacek et al. 2017; Lapko et al. 2018). In addition to using the Scanner by itself, there is also a need for understanding how different classes of circular strategies frameworks (e.g. macro, meso, micro, nano, networked) can best be used together.

9. Summary and conclusion

With this paper, we have contributed to the development of support tools for CE oriented innovation, or COI and to enable the translation of the CE concept in practice by creating support for visioning for CE. The contribution of this paper is four-fold: a) it provides an example of a process of how a circular strategies framework can be developed for a specific business type with the ability to support COI processes, b) it proposes a circular strategies framework for the manufacturing context, with c) an accompanying set of definitions of circular strategies, and d) it provides an example of how such a framework can be used in the early stages of a COI process. Next, it will be discussed how each goal was achieved and what the implications are for academia and industry.

In support of the first goal - to provide an example of the development of a circular strategies framework - this paper used the lens of Design Research Methodology (Blessing and Chakrabarti, 2009). This answered the call for the more deliberate and systematic development of circular strategies frameworks that are fit for purpose, voiced in Niero and Hauschild (2017) and Blomsma (2018). With manufacturing companies as the focus, it provided an example of how academia and industry can work together following a transdisciplinary approach (Sakao and Brambila, 2018) in developing resonant frameworks for specific audiences. The systematic development approach followed in this paper can be adapted and further expanded upon for other business types or other innovation contexts.

The second goal was achieved through the provision of the Circular Strategies Scanner. This framework can be used as a tool in COI and provides practitioners in manufacturing with a way of contextualising the CE concept, mapping current CE initiatives, and generating ideas for increased circularity. The third contribution, the set of circular strategies definitions included in the framework, served to support the consolidation of CE terminology and bringing academic and practitioner terminology closer together (Reike et al. 2018; Meste and

Cooper 2017; Kalmykova et al., 2018). This was achieved through drawing on both academic and practitioner perspectives with regards to these definitions in the development process. Together, these two points mean that an important iteration on the framework provided by Potting and colleagues was made, which brings more precision to the framework and which customises it for the manufacturing context. With this, the framework has been transformed from analytical framework into an innovation tool.

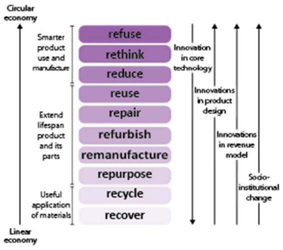
The fourth goal was achieved through illustrating how the Circular Strategies Scanner can be used in the early stages of a COI process to create a shared vision. The examples provided are of its application within businesses (see section 6). As well as with these companies, the Scanner was used with the other manufacturing companies participating in the CIRCit project. Specifically, it was used in the early stages of the action research, which allowed for a clear vision to be developed and establishing a clear direction for the work that followed, as it clarified with what aim different business activities relevant for COI needed to be deployed, whether this involved sustainability assessment, business model innovation, product design, digital technology strategies, the creation of take-back systems or value chain design.

Equally the Scanner could be applied across businesses, but also between business and academia, and beyond. In these contexts, the Scanner can serve as a boundary object where the stakeholders can clearly identify their activities or influence on different business processes across the life cycle, also enabling the comparison of CE initiatives and sharing of best practices.

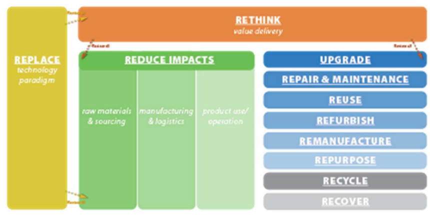
Acknowledgements
This article is one of the outcomes of the research project CIRCit (Circular Economy Integration in the Nordic Industry for Enhanced Sustainability and Competitiveness), which is part of the Nordic Green Growth Research and Innovation Programme (grant numbers: 83144) and funded by NordForsk, Nordic Energy Research, and Nordic Innovation. We would also like to thank the companies participating in the CIRCit project and the anonymous reviewers whose thoughtful feedback aided the development of this work.

Appendix A

Overview of changes to adapt the Potting et al (2017) framework for the manufacturing context



Adapted into:

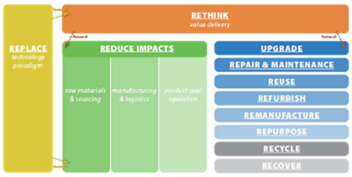


Major adaptations - changes in the structure of the framework		
#	In Potting et al (2017):	First version of Circular Strategies Scanner:
1	Circular strategies organised hierarchically: ranging from those that are considered more linear to those that are increasingly more circular.	Circular strategies are organised according to the business functions they apply to, in five main areas: *Replace*, *Rethink*, *Reduce Impacts* and two other operational process areas respectively containing end-of-use and end-of-life strategies
2	'Reduce' presented a single high-level strategy.	Specified into 'Reduce impacts' and the sub-categories of 'raw materials & sourcing,' 'manufacturing & logistics,' and 'product use/ operation.'
3	-	A visual structure consisting of three levels has been created to indicate the relationship of circular strategies, through the relative placement of the boxes containing the strategies, and the addition of arrows.
Medium adaptations - changes to the sub-groups or categories of the framework		
1	Inclusion of *Refuse* at the top of the hierarchy.	In the Circular Strategies Scanner, this strategy is understood as consisting of two sub-strategies and it was therefore split in two: *Refuse* (to abandon a practice altogether) and *Replace* (see Table 2). *Refuse* was subsequently not included in the framework, due to this framework targeting companies (see also Discussion section).
2	Contains the value driver: "Smarter product use and manufacture" for *Refuse*, *Rethink* and *Reduce*.	To refine this further, this value driver was split into "dematerialise/ combine functions" for *Replace*, "function & value proposition to market" for *Rethink*, and "improve circularity potential and efficiency" for *Reduce Impacts*.
3	Contains the value driver: "Extend lifespan of products and parts" for *Reuse*, *Repair*, *Refurbish*, *Remanufacture* and *Repurpose*.	To refine this further, this value driver was split in two to align with the end-of-use and end-of-life groupings as in line with Potting. As a result, *Upgrade*, *Repair & Maintenance* and *Reuse* are assigned the driver "Extending existing use-cycle," and *Refurbish*, *Remanufacture* and *Repurpose* are assigned the driver "Extending to new use-cycle."
Minor adaptations -- refinements in labels, definitions and the order of circular strategies		
1	Inclusion of *Recover*, as a strategy that refers to energy recovery through incineration, anaerobic digestion, pyrolysis.	The definition of *Recover* has been expanded to also include the recovery of biological nutrients and as such also covers such strategies as composting.
2	-	*Upgrade* was added to the framework to make explicit evolving quality and performance requirements of products.
3	*Reuse* comes before *Repair* in strategy order.	The order of *Reuse* and *Repair* was reversed, as Reuse that involves mere redistribution of products will – theoretically – maintain value to a higher degree with less added investment of resources, than redistribution that is also combined with repair activities.
4	Includes *Repair* as a circular strategy.	Repair was extended to also include maintenance, which is a common terminology in companies, and as such is indicated as *Repair & Maintenance* in the framework.

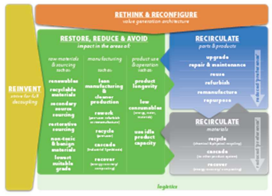
Table - This overview explains which changes were made to the Potting et al (2017) framework in order to adapt it to the manufacturing context. It gives a complete overview of the major, medium and minor adaptations.

Appendix B

Overview of changes to refine the 1st version of Circular Strategies Scanner and develop the 2nd version



Further refined into:



#	First version of framework	Second version of Circular Strategies Scanner:
Medium adaptations - changes to the sub-groups or categories of the framework		
1	The process of *Logistics* featured alongside *Manufacturing*.	*Logistics* is assigned a separate area in the framework, to better reflect that it covers all the operational process areas.
2	-	*Energy* was added as a relevant layer. That is: circular strategies should be considered with the intent to reduce overall energy consumption, and use clean(er) and renewable sources wherever possible.
3	Featured the strategy *Reduce Impacts*.	Label of strategy was changed to *Restore, Reduce and Avoid* to more fully reflect the range of strategies relevant for raw materials and sourcing, manufacturing and product use and operation.
4		Explicit addition of relevant strategies in *Restore, Reduce & Avoid.* Such as restorative sourcing (i.e. re-mining from landfill or using ocean plastics), lean and cleaner production practices and using idle product capacity. *Cascade* was also included: it can occur as Industrial Symbiosis and either as a secondary source sourcing strategy, or as a way of managing the co- and byproducts from manufacturing.
5	No detail provided regarding Rethink & Reconfigure.	To clarify the framework's relationship business models aspects, detail was added to the Rethink & Reconfigure category. This was done by drawing on Bocken et al. (2016) and Tukker's (2004) and adding the four main categories of Multi-flow offering, Long-life products, Access or availability, and Result and performance.
6	No explicit place for product and process design.	Product and process design are explicitly acknowledged by including them as box between Rethink & Reconfigure and the operational process of Restore, Reduce & Avoid and the Recirculate parts, products & materials.
Minor adaptations - refinements in labels, definitions and the order of circular strategies		
1	Value drivers largely based on Potting et al. (2019).	Value drivers were further refined: for *Reinvent* it was changed to "strive for radical decoupling," and for *Rethink* to "aim for business innovation for circularity," and for *Restore, Reduce and Avoid,* to "prevent excess, improve efficiency and aim for 'gentani' and improve circularity potential."
2	Visual structure consisting of three levels has been created to indicate the relationship of circular strategies, through the relative placement of the boxes, and the addition of arrows.	Visual layering emphasised through depicting it using the visual metaphor of physical layers, which takes the form of drop shadows and arrows to indicate the relationship between the process areas. Hierarchical relationships indicated by a single arrow, trade-offs and synergies by bi-directional arrows.
3	No indication of hierarchy of end-of-use and end-of-life strategies	Arrows were added to indicate the (theoretically) preferred application order of these strategies.
4	Headings only applied for *Replace, Rethink* and *Reduce Impacts.*	For consistency, all five process areas are given headings. End-of-use processes are titled *Recirculate – parts & products* and end-of-life processes are titled *Recirculate – materials*.
5	-	*Cascade* was added to *Recirculate – materials*. This adds the distinction between recycling – i.e. those processes that keep material circulating at or near virgin levels of performance, and cascades – i.e. those processes that extend the life of materials through allowing for reduction or redefinition of performance characteristics.
6		Addition of descriptors to strategies to aid in clarifying the type of application. For example: recycling can take place at the manufacturing stage, where it involves re-entering waste from the manufacturing process back into the process: pre-user recycling. It can also take place post-user at the *Recirculate – materials* stage, in the form of chemical or physical (mechanical) recycling.
7	Featured the strategy label *Replace*.	*Replace* was changed to *Reinvent - strive for full decoupling*, to prevent confusion in relation the replacing harmful chemicals with less harmful or benign ones. Moreover, this term better conveys the transformative nature of this strategy.
8	Featured the strategy label *Rethink value delivery.*	Changed to *Rethink & Reconfigure value generation architecture.*

Table - This overview explains which changes were made to the first version of the framework in order to develop the second and final version. It gives a complete overview of the medium and minor adaptations. No major adaptations were made at this stage.

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Developing a circular strategies framework for manufacturing companies to support circular economy-oriented innovation

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Abstract

This paper puts forward the Circular Strategies Scanner: a framework that introduces a taxonomy of circular strategies developed for use by manufacturing companies engaging in circular economy (CE) oriented innovation. Currently, a range of frameworks exists that propose a vision for how to operate in a CE, by identifying and organising relevant circular strategies. However, these frameworks have a limited applicability for specific business types, in particular manufacturing, and are unsuitable for use in CE oriented innovation, due to a lacking ability to support innovation processes through: 1) creating a comprehensive understanding of circular strategies, 2) mapping strategies currently applied and 3) finding opportunities for improved circularity across a range of business processes. This paper addresses these shortcomings by proposing a circular strategies framework for the manufacturing context, titled the Circular Strategies Scanner, which provides a comprehensive set of definitions of circular strategies and directly supports the early stages of CE oriented innovation. With this, the paper contributes to the body of work that develops CE transition methodology.

Keywords Circular strategies framework, closed loop, resource productivity, manufacturing companies, innovation.

1. Introduction

The linear economy is frequently characterised by the presence of structural waste: instances where components, products or materials reach their end-of-use/life prematurely, or where their capacity for value creation is underutilised. To address this, the circular economy (CE) concept proposes a range of efficiency and productivity enhancing activities collectively known as circular strategies, such as reduce, reuse, repair, recycle, restore, cascading, etc (EMF, 2013). In this sense, CE is an umbrella concept: it groups a range of sub-concepts and imbues them with a new meaning by highlighting a shared feature of the sub-concepts (Blomsma and Brennan 2017). This new meaning revolves around the notion that through the application of circular strategies both more value can be created (EMF, 2013) as well as value loss and destruction reduced (Murray et al., 2015).

Although CE has widely been recognised as an idea with potential merit, it has yet to be widely implemented and embedded within business and industry (Haas et al., 2015; Circle Economy 2019). This is in line with the progression of umbrella concepts: when the transformative potential of an idea has been recognised, the attention then turns to operationalising it through frameworks, tools, methods and approaches. This, in turn, allows for further examination of the concept.

For CE this means that there is currently a focus on developing CE transition methodology. This is taking place in a number of aspects relevant for Circular Oriented Innovation (COI) (Brown et al. 2019), such as in business models (Bocken and Antikanen 2018; Pieroni et al. 2019; Rosa et al. 2019), metrics and assessment (Kravchenko et al. 2019; Moraga et al. 2019; Saidani et al. 2019), product design (Moreno et al. 2016; Den Hollander et al. 2017) and the creation of organisational capabilities such as experimentation, value chain innovation and other human factors (Weissbrod and Bocken 2017; Chiappetta Jabbour et al. 2019; Nilsson-Lindén et al. 2019).

Previous academic work focuses on answering 'what' or 'how' to promote COI (Guzzo et al. 2019; Mendoza et al. 2017). However, supporting the early stages of COI through the establishment of a CE vision, i.e. answering

why to perform COI, has so far achieved relatively little scholarly attention. Finding the 'why' for a CE transition, requires understanding the type of structural waste in the system, which can be accomplished with a systemic analysis/diagnosis across life cycle stages and various business processes and knowledge areas. This requires various actors within and across business to define and explore problem and solution spaces together (Brown et al., 2019). Specifically, in COI a high-level conceptual understanding of CE needs to be translated into a vision that is useful and meaningful on the level of decision making (Hoffman, 2003; Boons and Howard-Grenville, 2009; Lindkvist and Baumann, 2014). The importance of a shared vision in innovation projects has long since been acknowledged (Pearce and Ensley, 2004; Bititci et al., 2004), and it has been posited to be relevant for both inter and intra organisational COI efforts (Brown et al., 2019).

Currently, there exists a range of frameworks that could potentially be drawn from to support CE visioning. These take the form of circular strategies frameworks, such as the ReSOLVE framework (EMF, 2015), the Performance Economy (Stahel ,2006), Cradle-to-Cradle™ (Braungart and McDonough, 2002), and the Waste Hierarchy (EC, 2008), but also the Ricoh Comet Circle™ (Ricoh, 2018), the Seven Fronts of Mount Sustainability (Interface, 2018). Importantly, these frameworks can be seen as the visual representations of a vision for how to operate in a CE, since they select, name and organise circular strategies seen as relevant, such that their relationship becomes apparent.

However, Mendoza et al. (2017), Reike et al. (2017) and Blomsma (2018) observed that such circular strategies frameworks can identify or emphasise different (groups of) circular strategies, which can be linked to addressing different types of structural waste. As such, there is a risk that they do not include circular strategies with transformative potential for a particular context. Moreover, Blomsma (2018) points out that little work has been done with regard to ensuring that frameworks are seen as relevant and useful by their intended audiences. For these reasons, there is scope to further develop these frameworks to support visioning in COI. Mendoza et al. (2017), Niero and Hauschild (2017) and Blomsma (2018) therefore call for the development of such frameworks within academia.

This paper answers this call and addresses the question of how to develop circular strategies frameworks such that they are relevant for their intended audiences, in a manner that points to the transformative potential of CE and that assists with unpacking the complexity associated with COI. With this, this paper contributes to the body of work that develops CE transition methodology, focussing on the early stages of COI and engaging the affected audiences in a transdisciplinary approach (Sakao and Brambila, 2018).

As an illustrative case, we develop a circular strategies framework for manufacturing companies1. Manufacturing companies were chosen as the focus as they are important users of materials and energy, produce significant amounts of byproducts traditionally regarded as waste, and form an important employment sector2 and contributor to GDP (Rashid et al., 2013). In addition, manufacturing companies play an important role in the creation of value to their customers and therefore have great potential to decouple this value provision from linear resource consumption.

After clarifying the research gap in the background section and exploring the shortfalls of current circular strategies frameworks to support COI within manufacturing, we continue with setting out the methodology applied in this paper. In the following sections we present the development of the criteria used for designing the new framework and explain the relevant details and outcomes of each subsequent development phase. Furthermore, in section 6, we provide an example of application of the framework in COI. We close with a discussion of the contributions of this paper and directions for further work.

[1] We use the expression *manufacturing companies* to refer to secondary manufacturing, as opposed to primary production. Moreover, these companies are not contract manufacturers, but have a degree of control over their supply chain.
[2] Sector, as used here, refers to an area of economic activity such as food, medicine, construction, etc. See: https://unstats.un.org/unsd/classifications/.

2. Background and research clarification

Describing the complete landscape of circular strategies frameworks is beyond the scope of this paper. However, here we provide an overview of the current landscape of circular strategies framework, through offering a typology of five classes of frameworks. The first four classes describe a continuum where the scope becomes increasingly smaller: (1) the macro level of industrial systems or economies; (2) the meso level of sectors, materials and business types; (3) the micro level of companies; and (4) the nano level covering product (groups) (Saidani et al., 2017). The fifth level adds the layer of (5) networked and regional approaches, through which the other four levels are connected. See Figure 1.

Overview of the landscape of circular strategies frameworks

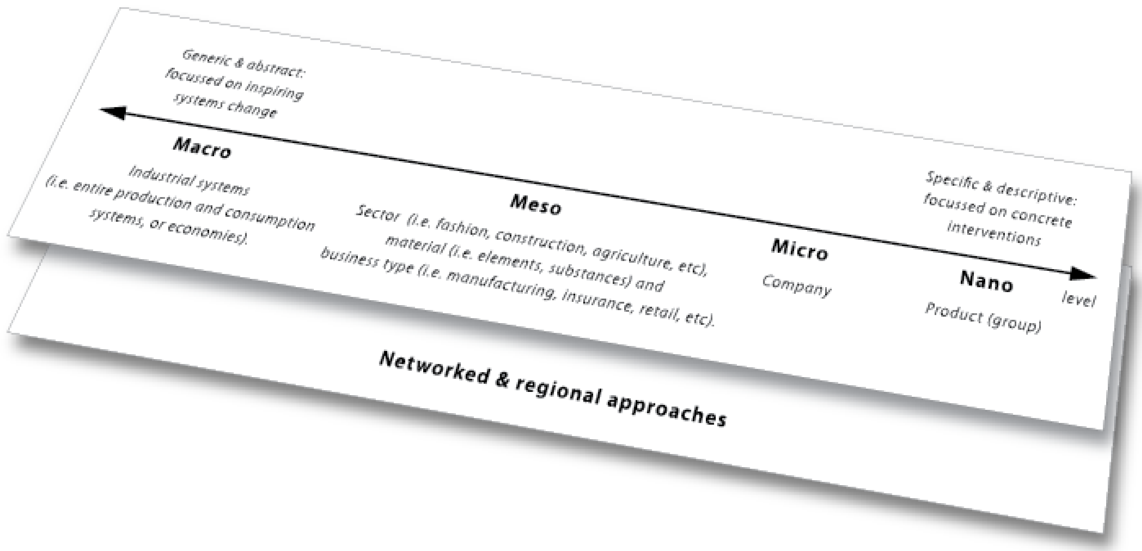


Figure 1. Schematic illustrating the coverage of frameworks on the macro-meso-micro-nano scale, and their relationship with frameworks covering networked and regional approaches.

Considering the landscape of current circular strategies frameworks, a number of observations can be made that explain why current circular strategies frameworks fall short in their capacity to support visioning for manufacturing. First, a circular strategies framework needs to create a comprehensive understanding of circular strategies, as relevant for the purpose (Brown et al., 2019) and context (Blomsma, 2018). Think, for instance, of the difference in the main functions of insurance and finance firms, retail and wholesale businesses, service providers, and manufacturing companies. Different circular strategies will be relevant in these contexts (Rashid et al. 2013; Johannsdottir 2014; Upadhyay et al., 2019).

Currently a multitude of frameworks exist on all levels of the landscape. See for frameworks on the macro level, for example: Allwood et al. (2011), Reike et al. (2018), Bocken et al. (2016), or Braungart and McDonough (2002). Likewise, for meso level frameworks for materials, see for water (WssTP, 2015) and biomass (ECN, 2018); or fashion and textile frameworks by EMF (2017), Inditex (2016) and Mistra Future Fashion (2018). On the micro level, consider: Gispen’s (2018) framework for circular furniture, *The 10 R’s of Circularity* by (Mitsubishi Electra, 2018), the Ricoh Comet Circle™ (Ricoh, 2018) (first used in 1994), or the framework used by Konecranes (2018). Likewise, on the nano level: Circular Jeans by Levi Strauss & Co. (2015), and Re-Entry for carpet tiles (Interface, 2016). Lastly, on the networked level, consider: Ehrenfeld and Gertler, 1997; Aguinaga et al., 2018; Pauli, 2010.

A notable exception of circular strategies frameworks exists on the meso level that apply to specific business types, in particular to manufacturing. One exception is the ResCom framework by Rashid et al. (2013), which targets manufacturing companies. However, this framework is also not well suited to supporting innovation processes, as it includes few circular strategies and contains a limited consideration of business processes.

In addition to creating a comprehensive understanding of circular strategies, a circular strategies framework that supports visioning needs to both map strategies currently applied as well as find opportunities for improved circularity for a range of business processes from a systemic point of view. In this aspect, current frameworks are also lacking as they are often derived or compiled to serve as a summary or overview of a piece of (mostly theoretical) work, as opposed to being purposefully developed for use in COI in and with businesses (Niero and Hauschild, 2017; Kalmykova et al., 2018; Blomsma, 2018; Sakao and Brambila, 2018). However, to establish a vision it is important to both understand the current situation - e.g. what is already being done towards CE, or what capabilities provide a basis for this, as well as to identify what opportunities are present and desirable. Current circular strategies frameworks are not designed to capture an overview of both the current situation and ideas for future innovation.

Another shortcoming of current circular strategy frameworks is that they exhibit ambiguity with regards to the meaning of and relationships between the included circular strategies, allowing the same term to adopt multiple meanings - sometimes with radically different outcomes from a resource perspective (e.g. whether recycling keeps material quality on a consistently high level, or whether it represents downcycling) - or to be rendered inapplicable to some contexts (Reike et al., 2018; Blomsma, 2018).

This paper addresses these shortcomings, by a) providing an example of a process of how a circular strategies framework can be developed for a specific business type with the ability to support COI processes, b) proposing a circular strategies framework for the manufacturing context, resulting in the Circular Strategies Scanner, with c) an accompanying set of definitions of circular strategies (including commonly used synonyms). In addition to this, we provide d) an example of how such a framework can be used to structure and guide the early phases of COI, in order to show the relevance of visioning approaches within CE transition methodology.

3. Methodology

Design Research Methodology (DRM) was applied for the development of the new circular strategies framework for manufacturing, as this method is particularly suited to the deliberate iteration of methods and tools (Blessing and Chakrabarti, 2009). Next, a high-level overview of the aim and activities in each phase is provided. See Figure 2 for an overview: more details are provided in the sections dedicated to each respective phase. The development of the proposed framework took place from November 2017 to July 2019.

Research clarification - This phase, already discussed in the previous section, served to refine the research gap and identify the need for a framework specifically for manufacturing companies.

Descriptive study I - This phase served three goals. First, a list of circular strategies to be included in the framework was compiled. Second, criteria that could be used to guide the development process of the new framework were articulated, which, third, were used to choose an existing framework as the basis for the development of the new framework. A series of workshops and meetings were held for this purpose. Iterations of the strategies list, their definitions and the framework requirements were performed throughout the project, but are presented as a single phase for clarity and brevity.

Prescriptive study I - A series of workshops and follow-up meetings were held to conceptualize and develop a first version of the circular strategies framework, as well as the corresponding clarifications and elaborations on strategies, and the relationship between them.

Descriptive Study II - In this phase the applicability and usefulness of the framework in the context of the manufacturing sector was evaluated and improvement opportunities sought. Workshops were performed with three manufacturing companies from the heavy machinery, electronics and furniture sector.

Prescriptive study II - A series of meetings was held to discuss the implementation of the improvement opportunities, based on insights from *Descriptive Study II* and the iterations of the *Research Clarification* and *Descriptive Study I* phases. A second version of the framework and a final list of strategies and their definitions were developed during this phase.

Moreover, the approach applied was deliberately transdisciplinary. That is, it aimed for establishing "a common system of axioms for a set of disciplines," which was achieved in two ways (Sakao and Brambila-Macias, 2018:1400), see also Figure 2:

(1) *Adopting a systemic view* - In the context of (more) circular manufacturing this means the alignment of the different business processes, which together contribute to the creation of circular systems. The perspectives of these processes therefore need to be included.
(2) *Inclusion of non-academic stakeholders* - Creating (more) circular manufacturing systems entails affecting changes in manufacturing companies. As such, it is important to acknowledge the perspective of manufacturing companies in the development of the new framework.

The first type of transdisciplinarity was implemented through the creation of the CIRCit research consortium[3] to represent the knowledge related to business model strategy, product design, and a range of operational processes such as sourcing, manufacturing, logistics, through-life support, digital technologies and end-of-life operations, but also sustainability aspects and value chain management.

The second type of transdisciplinarity was implemented through application of the framework on retrospective company cases, as well as applying the framework in ongoing research that is actively supporting companies in implementing circular practices. Furthermore, the consortium contained representatives of the interests of manufacturing companies, such as industry associations. Through this, the perspective of 'real-world' considerations was added. Next, the outcomes of each phase is presented.

[3] See for more information about the consortium: www.circitnord.com.

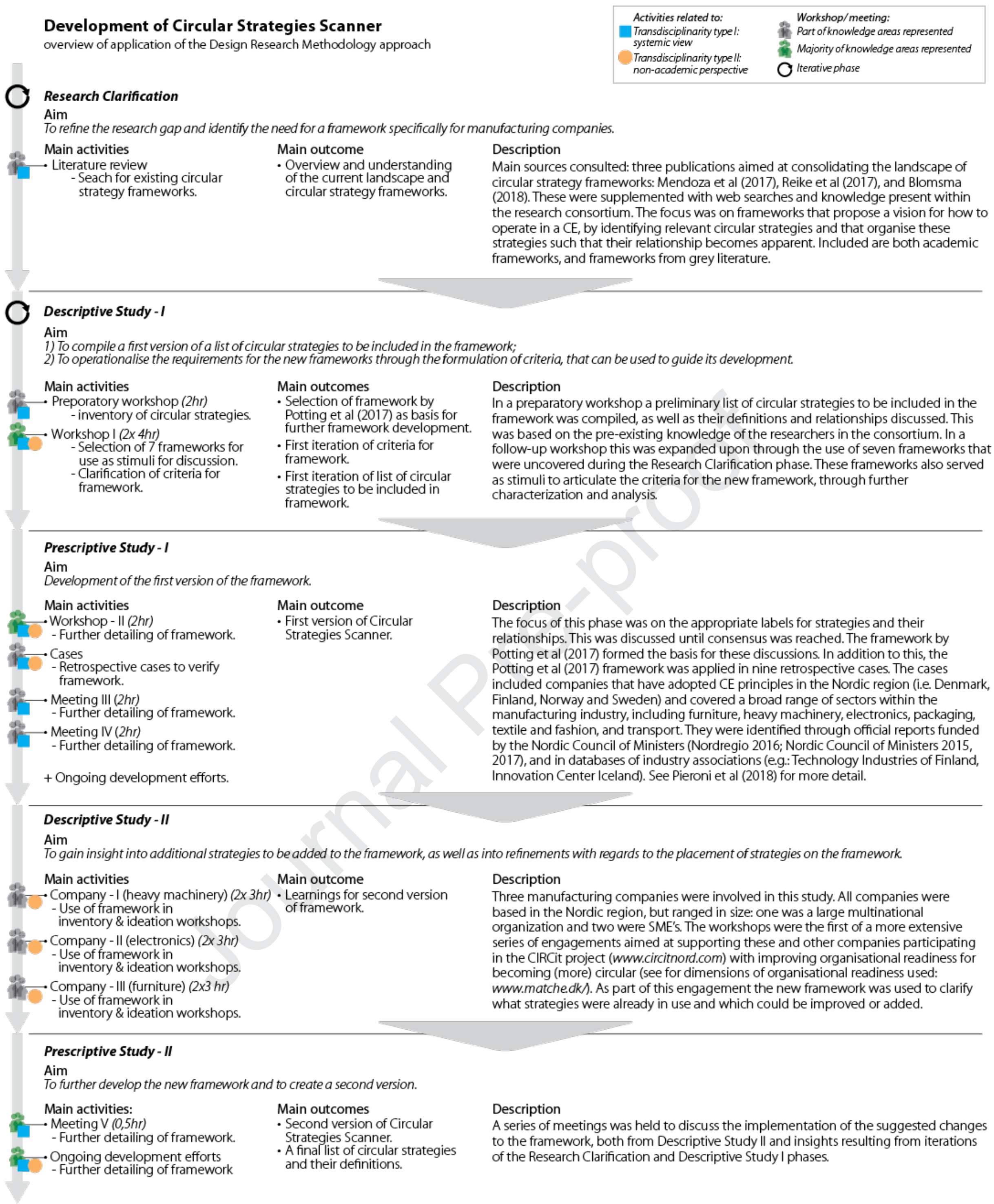


Figure 2. Schematic illustration of the approach followed for the development of the Circular Strategies Scanner.

4. Descriptive Study I - criteria for a circular strategies framework for manufacturing companies

This phase served to establish a foundation for the development of the new framework. This was done in the following manner, see also Figure 2.

4.1. Rationale behind Descriptive Study I

Due to the lack of suitable meso level frameworks with a business type orientation, macro frameworks were used as a starting point with the aim to adapt their generic applicability and generative capacity for manufacturing companies. From the macro frameworks 1) relevant circular strategies were extracted, and 2) criteria that could be used to guide the development process of the new framework were articulated, which 3) were used to choose the best fitting existing framework as the basis for the development of the new framework. In particular, seven macro level frameworks uncovered during the Research Clarification phase were used: Thierry et al. (1995), Parkinson and Thompson (2003), Allwood et al. (2011), Bocken et al. (2016), Nussholz (2017), Potting et al. (2017), and Blomsma (2018). These were included based on 1) their range of relevant strategies for the manufacturing context, 2) their inclusion of definitions and/or examples of these strategies and 3) representing a broad range of approaches to classify or organise the strategies in relation to each other. This served to have contrasting definitions and approaches that could be discussed and analysed.

4.2. Outcomes Descriptive Study I

The final version of the list of included strategies, their definitions and examples, which continued to be iterated throughout the development of the framework, can be found in Table 2 (see section 7. *Prescriptive study II*). Here, the focus is on the five criteria for the new framework that were developed to detail the main functions of a circular strategies framework (create understanding of CE, map current CE initiatives, generate ideas for increased circularity). The criteria were iterated until they represented five clear requirements for the development of the new framework. This section concludes with the selection of the best fitting existing framework.

Criterion #01: A tool for inspiring, motivating and aligning people

In innovation processes it is important to invoke relevant frames, acknowledge cognitive principles (which involve cognitive limits, but also principles of attention, inspiration and motivation) and, in collaborative settings, to consider the alignment of understanding, mindsets and interests between different stakeholders. Language, both visual and written, plays an important role in this: it helps directing attention, summarising and synthesising information from internal and external knowledge sources and it supports orientation towards relevant aspects of the context (Biloslavo et al., 2018; Breuer et al., 2018) and in the creation of a shared vision, also in the context of CE (Blomsma, 2018). Therefore, in line with the frameworks discussed above, the proposed framework should 01) represent a complex phenomenon in an easily accessible manner in order to inspire, motivate and align people.

Criterion #02: A tool for describing current situations and identifying opportunities, both incremental & transformative

A framework suitable for use by a wide variety of manufacturing businesses, cannot be broad in the sense of the frameworks on the macro level, as it will lose relevance. At the same time, it can also not be specific in the sense of the company and product frameworks, as this would mean it is limited in its reach and impact. However, the new framework should be suitable for describing both current initiatives and have the capacity to systematically explore relevant strategies and identify new opportunities. As such, the new framework should balance the strengths of the macro and meso level frameworks - which are generative and allow for the exploration of alternatives, with that of the micro and nano level frameworks - which offer greater specificity in relation to the context in which strategies are applied. Thus, the new framework should: 02a) balance the generation of new ideas, with that of describing existing situations. This indicates that it is preferable to include a diverse set of circular strategies, as opposed to high-level aggregated groups of strategies.

Furthermore, opportunity finding needs to point to the potential for improving existing strategies, as well as to radically different ways of achieving goals and creating, delivering and capturing value. This can involve the design, production and/ or transport of physical products, but it can also require a change in the business logic and operations that changes how products are commercialized and consumed. Think of the implementation of access-over-ownership models, or radical dematerialisation through a change in paradigm. As such, the framework should 02b) provide an overview of the spectrum of available strategies ranging from incremental to transformative. This indicates that the set of included strategies should cover strategic as well as operational business processes.

Criterion #03: A tool for facilitating alignment of changes in business processes and capabilities
Circular strategies frameworks aimed at specific business types need to provide insight into which business processes relevant for that business type need to be aligned. This means, following Allwood et al. (2011), Potting et al. (2017) and Reike et al. (2018), that the new framework should indicate which circular strategies may apply to which flows. In the manufacturing context, this implies 03) indicating which strategies affect which business processes and related capabilities.

Criterion #04: A tool for bringing together efficiency and effectiveness strategies, and strategy configurations
Following e.g. Pauli (2010), Stahel (2006), Potting et al. (2017), Reike et al. (2018) and EMF (2015), we adopt the view that both resource-efficiency and resource-effectiveness are important in the manufacturing context. The new framework therefore should: 04a) explicitly include the reduction and avoidance of resource use and impacts, as well as resource productivity strategies aimed at continued use and value delivery.

Moreover, many manufacturing companies operate in complex scenarios, that can be thought of as circular configurations: situations where two or more circular strategies are present (Blomsma and Brennan 2017, Blomsma 2018). Think of product/ service systems where direct reuse, but also repair, refurbishment and remanufacturing are taking place, in addition to the recycling of materials. As such, the proposed framework should: 04b) allow for generating insight into circular configurations.

Criterion #05: A tool for alignment with drivers: value creation & capture orientation
Businesses need to create and capture value to continue their activities. It is widely acknowledged that circular strategies have the capacity to contribute to this. However, not many current frameworks support the identification of the type of value that can be captured through which strategies. The new framework therefore needs to be aligned with the perspective of systemic value creation and capture. Support in identifying this can enable assessing and measuring outcomes and tracking potential deviations from the planned future state, which is fundamental to transition management (Breuer et al., 2018). As such, the proposed framework: 05) has to point to the value drivers that circular strategies can contribute to. That is: the framework has to help users identify relevant contributions to value creation and capture, such as improved efficiencies, supporting optimal use during the use phase, and value recovery opportunities, resulting in either financial or non-financial gains within or outside the company (Circle Economy et al., 2016). As these may be relevant for business shareholders, but also suppliers and customers, the environment and society they need to be formulated such that relevance for these stakeholders can be easily appreciated.

Next, the seven frameworks were compared and rated on these criteria, see Table 1. Although none have a perfect score, the framework by Potting et al. (2017) scores the highest: it represents a complex phenomenon in an easily accessible manner (criterion 01), contains a comprehensive set of circular strategies (criterion 02b), includes efficiency as well as effectiveness strategies (criterion 04a) and points to value drivers that circular strategies can contribute to (criterion 05). This framework was therefore chosen as a basis for further development of the new framework, with its relevance for different business processes and capabilities (criterion 03) identified as in need of further improvement.

Criteria The new framework should:	Bocken et al (2016)	Allwood et al (2011)	Parkinson & Thompson (2003)	Thierry et al (1995)	Potting et al (2017)	Nussholz (2017)	Blomsma (2018)
01) A tool for inspiring, motivating and aligning people.	+	++	0	++	++	+	+
02a) Balance the generation of new ideas, with that of describing existing situation.	0	+	0	+	++	+	0
02b) Provide an overview of the spectrum of available strategies ranging from incremental to transformative.	+	+	0	+	++	++	0
03) Indicate which strategies affect which business processes.	0	+	0	+	+	0	0
04a) Explicitly include the reduction and avoidance of resource use and impacts, as well as resource productivity strategies aimed at continued use and value delivery.	+	+	0	0	++	++	0
04b) Allow for generating insight into circular configurations.	+	++	0	++	++	+	+
05) Has to point to the value drivers that circular strategies can contribute to.	++	0	0	+	++	+	++
+++ = framework satisfies criterion very strongly, ++ = framework satisfies criterion strongly, + = framework satisfies criterion moderately, 0 = framework doesn't meet criterion or only marginally.							

Table 1 - Comparison of the seven frameworks that were used in Descriptive Study I using the development criteria.

5. Prescriptive Study I

During this phase the first version of the new framework was developed, through adding detail to Potting et al. (2017) as relevant for the manufacturing business type, guided by the criteria established in the above and the exploratory case studies (see Pieroni et al., 2018). The focus was on the appropriate labels for strategies, and how to convey the relationship between the included strategies.

5.1. Outcomes Prescriptive Study I

The outcomes of this phase is discussed in terms of the adaptations of the Potting et al. (2017) framework that were made. Only the major adaptations are elaborated upon: see for the first version of the framework Figure 3 and the complete set of changes Appendix A. See for definitions and examples of individual strategies Table 2 (section *7. Prescriptive study II*).

Major adaptations #01 and #02: Organisation of circular strategies according to business processes, and greater specificity for 'Reduce'

The preliminary list of circular strategies from the previous phase was organised according to the business processes as typically found in the manufacturing context, to meet criterion #03. For this, the process of transformation of raw materials into finished or intermediate goods was divided as follows. First, two areas that are related to the corporate strategy were identified: the first is changing the paradigm of practices and was named 'Replace,' and the second is a reconsideration of how value is delivered, entitled 'Rethink.' The former strategy enables radical dematerialisation through different ways of performing functions (e.g. functional replacement or new practices), which can be enabled by new technologies. This strategy was renamed from Potting and colleagues' 'Refuse' (see Medium adaptation 1 in Appendix A). The latter strategy involves new business models that are more resource efficient, such as access-over-ownership offerings, enabled by commercial models based on leasing, renting or pay-as-you-go. As such, 'Replace' concerns the

delivery of functionality through radically different means, whilst 'Rethink' delivers similar functionality through different customer relationships and which may involve a redefinition of the functional unit.

The remainder of the framework concerns operational processes. Potting et al's (2017) 'Reduce' was further divided to make its application to the following operational processes explicit: 'Raw materials and sourcing,' 'Manufacturing and logistics' and 'Product use/ operation.' This indicates that in these phases, the focus is on efficient use of resources and the reduction of harmful impacts.

The next two operational process areas respectively contain various end-of-use and end-of-life strategies. The first contains the strategies 'Upgrade' (see Minor adaptation 2), 'Repair & Maintenance' (see Minor adaptation 4), 'Reuse,' 'Refurbish,' 'Remanufacture,' and 'Repurpose'; and the second which contains the strategies 'Recycle' and 'Recover' (see Minor adaptation 1).

Major adaptation #03: Addition of the relationship between business processes

To capture the different relationships between the strategies (criterion 04b), a visual structure consisting of three levels has been created: the first occupied by 'Replace,' the second by 'Rethink' and the third by the remaining strategies. This is indicated by the relative placement of the boxes containing the strategies and the addition of arrows. This signals that, within the manufacturing context, some relationships between circular strategies are of a hierarchical nature, and some exist in the form of trade-offs and synergies. An example of a hierarchical relationship: 'Replace' may preclude the use of certain other circular strategies, when, for instance, a physical product is replaced by a virtual service. On the other hand, the application of 'Rethink' can require the support of repair and maintenance strategies to be viable, such as in certain product/service system offerings. As such, the application of either 'Replace' or 'Rethink' requires that the relevance of all strategies on the levels 'below' should be evaluated, as their relevance may change when these strategies are applied.

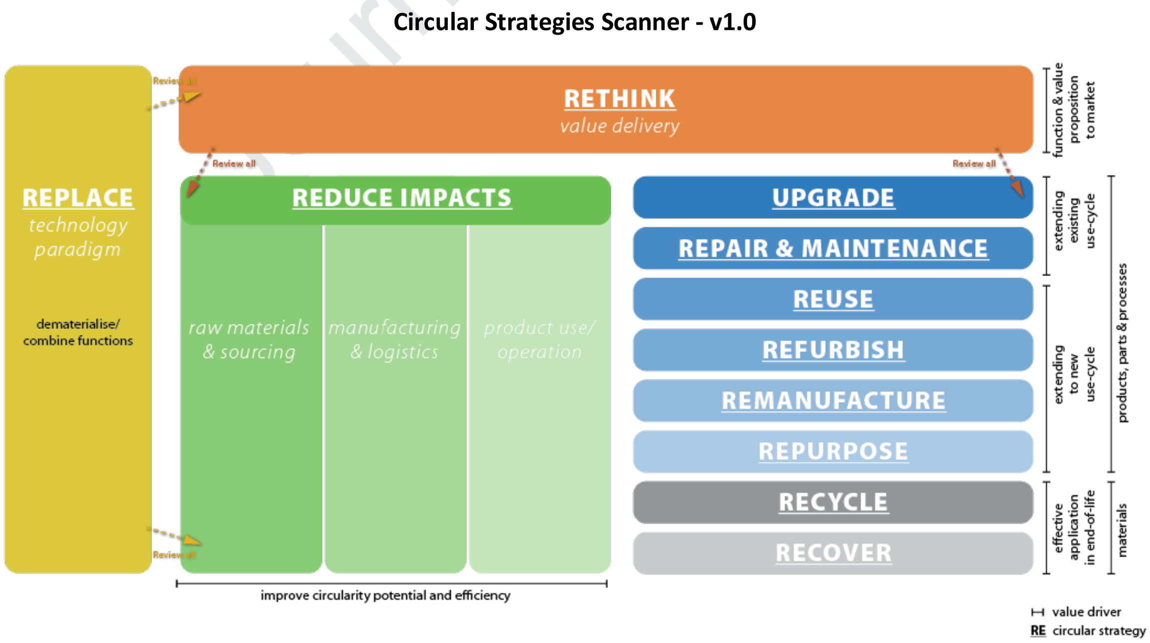


Figure 3 - The first version of the Circular Strategies Scanner.

Examples of other relationships include trade-offs: the choice, for instance, for certain durable materials such as composites may impede recycling. In this case, a strategy that facilitates product longevity, conflicts with recycling the material at the end-of-life. On the other hand, certain interventions may cause cumulative or

reinforcing effects, such as choosing a renewable material that at the end-of-life can be safely composted, allowing this single intervention to cover two circular strategies synergistically; the sourcing of materials that can be renewed and the 'recovery' of nutrients at the end-of-life. For this reason, the strategies that reduce impacts and that affect end-of-use/ life are placed on the same 'level.' When considering these strategies, therefore, it should be examined if trade-offs and/ or synergies with other strategies on this level exist.

With this structure the new framework departs from the hierarchy that Potting and colleagues use. However, the value drivers have been preserved and further refined, in line with the different business processes (see Medium adaptations 2 and 3).

6. Descriptive Study II

In this phase the framework was tested in workshops within three manufacturing businesses from the heavy machinery, electronics and furniture sectors. The aim was to gain insight into additional strategies to be added, as well as into refinements with regards to the placement of strategies. Moreover, this section provides an example with regards to how a circular strategies framework can be used in the early stage of COI.

6.1. Use of the new framework in workshops in Descriptive Study II

With each business a two-part workshop was carried out. The first part mapped the circular strategies currently applied within a product or service (category). Participants were asked to prepare by classifying their offering (products, services or PSS), and to identify and describe the strategies currently applied. In the workshop, all strategies were mapped onto the Scanner and discussed: the current implementation level of the strategies, as well as their respective affinities to the business and their resource efficiency impact (e.g.: percentage of total sales or revenues, percentage of sold products recovered for end-of-use/life treatment). The second part of the workshop focused on scanning for new opportunities to enhance or append additional strategies, through the evaluation of the current state and the identification of gaps and improvement hot spots. Case examples of other companies employing strategies across the full range of strategies covered by the Scanner were used to stimulate the discussion with participants.

In total, each workshop lasted approximately six hours and involved participants with diverse skills and expertise, such as marketing and sales, services and product development, after sales and customer services, operations, corporate social responsibility, IT, business strategy and finance. Moreover, representatives from the business leadership or top management participated in all workshops. The number of participants varied from three to ten, according to the business size.

6.2. Outcomes Descriptive Study II

An example of the mappings created in both phases of the workshop can be found in Figure 4. The top part represents individual initiatives currently applied by one of the companies (one initiative per number). This represents current CE initiatives or current capabilities that can contribute towards increased circularity. The bottom represents improvement areas: circular strategies that could be improved or scaled up, or strategies that could feasibly be added. Comparing the current state with new opportunities, it can be seen that ideas were generated that increased the coverage of circular strategies, some even developing into more advanced concepts when synergies between circular strategies were identified.

During the workshops with the companies, the framework functioned as a boundary object (Star and Griesemer, 1989) for different participants to align their perceptions. That is: clarifying the current state together allowed participants to build a common picture of their organisations' ongoing CE initiatives and current capabilities, and to align their understanding of their nature and maturity. Moreover, the shared

exploration of new opportunities helped the participants to share their perceptions of these opportunities, and set priorities for their innovation pipeline. In all cases the visioning exercise helped to identify why and where to focus, whether in relation to the development of circular business models, applying circular product design principles, the application of smart technologies, the assessment of potential initiatives in relation to their sustainability impact and/ or areas where collaboration with other stakeholders needed to be sought[4]. As such, this visioning exercise facilitated with the Scanner served to guide and direct the COI process to relevant initiatives and appropriately set the scope for these efforts early on. Direct feedback provided by individual participants supports this. Representative responses were “quite helpful”, “great tools” and “visualization with the boards helped the conversation a lot.”

However, observations were made that were used to improve the framework further. First, it was noted that efficient logistics is relevant throughout a product’s life, and not just before, during and after manufacturing. That is: for operations extending existing life cycles or those that extend the product life to new use-cycles and in recovering materials for end-of-life treatment, logistics must be cost- and carbon efficient. It should be placed in such a way to indicate this broader relevance.

Moreover, it was observed that it is also possible to use the sourcing stage as an opportunity to recapture waste that has already entered the environment. The various projects around recovering plastic from the oceans are examples of this (The Ocean Cleanup 2018, Plastic Oceans 2018), and the framework should also highlight the possibility of sourcing such materials. These observations led to the Medium adaptations 1 and 2 discussed in the next section, see also Appendix C.

[4] For more on this, see the CIRCit website (circitnord.com).

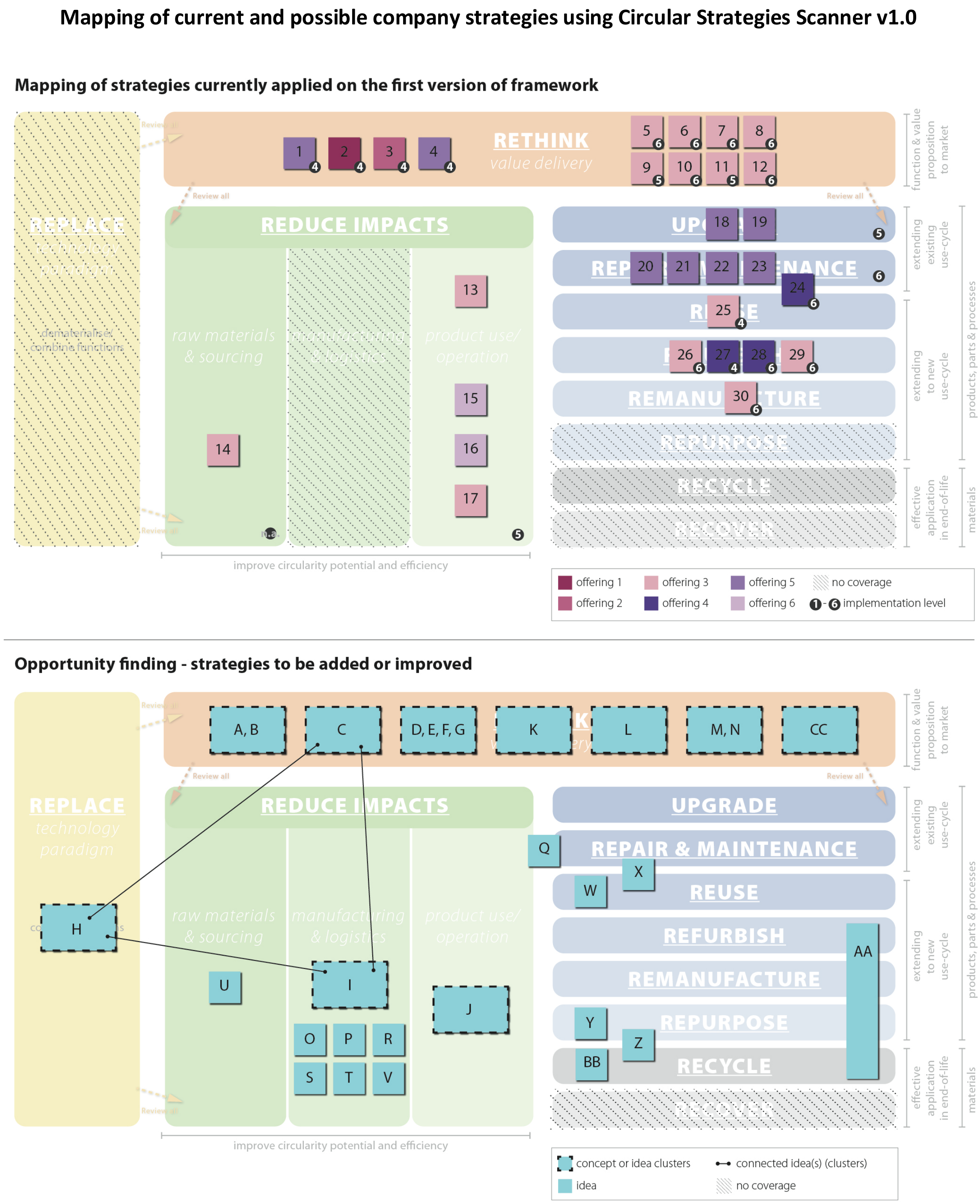


Figure 4 - Example of how the first version of the Circular Strategies Scanner was used in a two-part workshop with one of the companies participating in the CIRCit project. One or double letters are used per strategy: connected or grouped ideas represent closely related ideas that together constitute a new concept. Results are anonymised for reasons of confidentiality.

7. Prescriptive study II

The aim of this phase was to develop a second version of the framework on the basis of the identified improvement opportunities. The main activities were ongoing development efforts, supplemented by a series of meetings held to discuss the implementation of the suggested changes stemming from *Descriptive Study II* and the continued iteration of the *Research Clarification* and *Descriptive Study I.*

7.1. Outcomes Prescriptive Study II

No major adaptations were made, therefore the focus here is on medium adaptations: see for the second version of the framework Figure 5 and the complete set of changes Appendix B. See for definitions of individual strategies Table 2.

'Logistics' was assigned a separate layer such that it encompasses all the operational process areas. In addition to this and in a response to additional sources considered, 'Energy' was added as a layer encompassing all circular strategies (Cullen, 2017; Mestre and Cooper, 2017). That is: circular strategies should be considered with the intent to reduce overall energy consumption, and the use of clean(er) and renewable sources wherever possible.

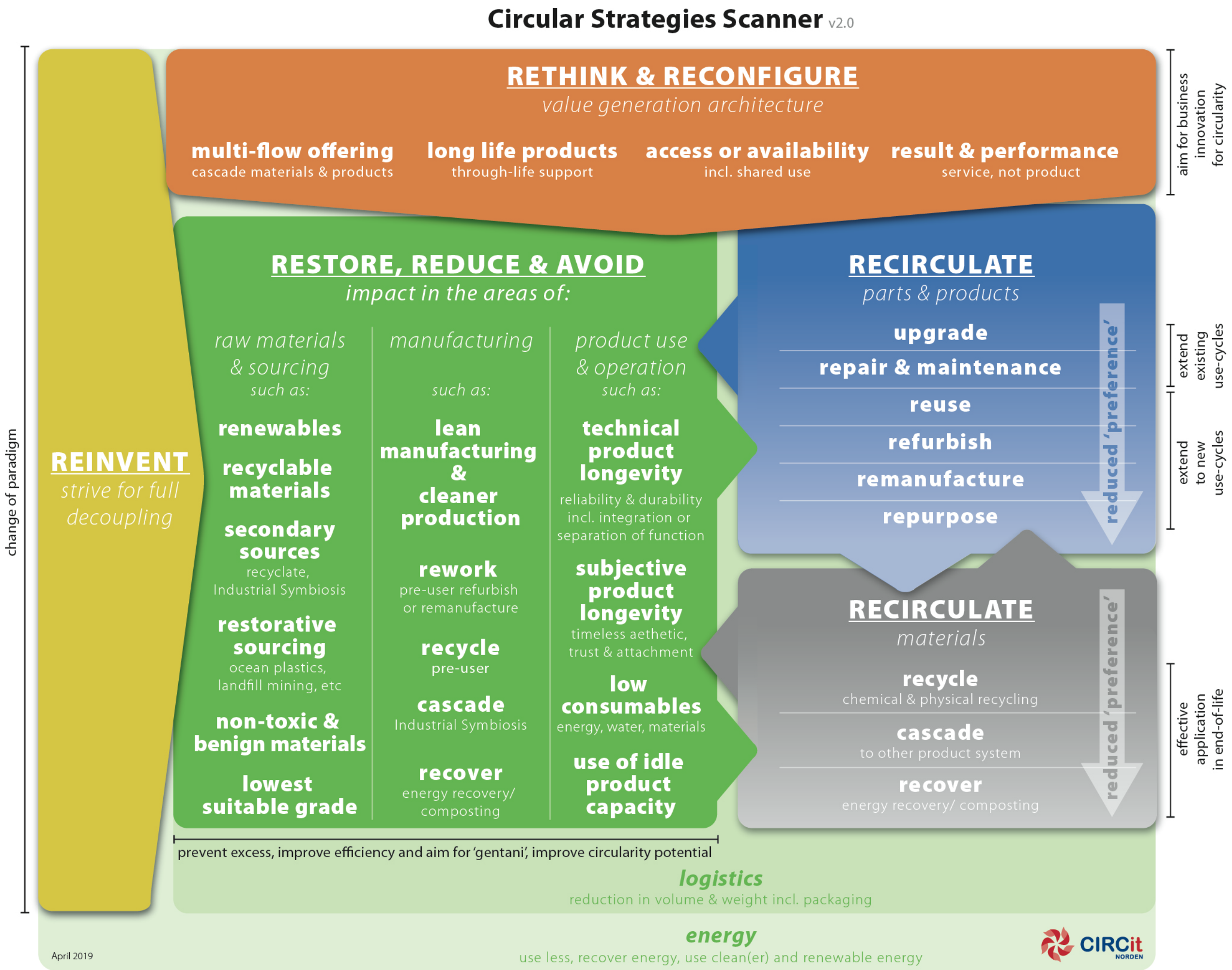


Figure 5 - The second version of the Circular Strategies Scanner.

Moreover, the heading 'Reduce impacts' was changed to 'Restore, reduce & avoid' to more fully reflect the range of strategies relevant for raw materials and sourcing, manufacturing, and product use and operation.

Also, more detail was added to the visual representation of the framework, which entailed the addition of suggested strategies in this area (see Minor adaptation 2). These strategies are meant to be inspirational, rather than exhaustive. In some cases this resulted in allocating strategies to multiple places in the framework, which is in line with Potting et al. (2017) and Reike et al. (2018). Recycling, for instance, can be found in both the category Restore, Reduce and Avoid, as well as in the category Recirculate - Materials. This reflects the fact that pre- and post consumer recycling can take place. Similarly, cascading, or industrial symbiosis can take a variety of different forms: as a sourcing strategy, as a way of valorise manufacturing waste, but also as an end-of-life strategy for materials. These multiple occurrences are also due to departing from the hierarchical structure used by Potting et al. (2017) (see also section *5. Prescriptive Study I*). For clarity descriptors have been added to signal the specific application of a strategy (see Minor adaptation 3).

Similarly, detail was added to the Rethink & Reconfigure category to clarify the framework's relationship with business models aspects. Two sources were consulted for this: Bocken et al. (2016) and Tukker (2004), chosen because of their seminal importance in the CE field (Pieroni et al. 2019) These respective typologies were synthesised into four main categories that cover circular business model strategies available to manufacturers and that represent a fundamental change to the logic of how such a business operates: 'Multi-flow offering,' 'Long-life products,' 'Access or availability,' and 'Result and performance.' This, as opposed to including strategies that are more appropriately thought of as supporting operational strategies such as efficiency and encouraging sufficiency.

Strategies included in the Circular Strategies Scanner (further developed from Potting et al. 2017)

Driver	Strategy Synonyms	Area of application or sub category Recirculation strategy & synonyms *Definition (specifics)* • Example practice(s)/ specifics
Enable smarter business concepts through striving for full decoupling.	**Reinvent** Refuse	**The paradigm** *Make physical products redundant by offering the same function or combined functions, usually enabled by radically different product, technology or both (Potting et al. 2017).* • The 'bring-your-own' movement facilitates replacing such single use items such as coffee cups. • Music and video streaming services negate the need for data carriers such as CDs and DVDs. • Multi-functional devices such as smart phones combine the functionality of multiple devices (camera, GPS, phone, calculator, alarm clock, sound system, computer) in a single device.
Enable smarter business concepts through business model innovation for circularity. Products tend to not radically change, although the technology can evolve.	**Rethink & reconfigure** Revolution Replace	**Business models** Multi-flow offering – cascade materials, parts & products *Extend the life of materials or products in a manner that exploits their residual value and becomes a significant part of the offering of the business. May involve providing new forms of value (Bocken et al., 2016).* • Leesmap (magazine subscription where the price decreases with the age of the magazines). • British Sugar (from the core-business of sugar, to also selling many different co-products). Long life products – through- life support *Extend the life of products through offering support during their lifetime (Tukker, 2004).* • Provision of maintenance, offering of repair services, or sales of spare parts. Access or availability – incl. shared use *Satisfying user needs without transferring ownership of physical products. Instead, user or consumer pays for access to the product for a certain period of time (Tukker, 2004).* • Bike or car sharing services (e.g. Bycyklen in Copenhagen, Santander Cycles in London, and many other cities around the world; Drive Now, Green Mobility, Zipcar, Blablacar). • Clothing rental and subscriptions (e.g. Rent the Runway, Vigga, Mud Jeans). Result & performance – service, not product *The provider of the service delivers an outcome for the customer (Tukker, 2004).* • Performance contracts (Rolls Royce - Power by the Hour).
Prevent excess, improve efficiency and aim for 'gentani', improve circularity potential.	**Restore, reduce & avoid**	**Raw materials & sourcing** *Improve circularity potential and efficiency in the sourcing process (Mestre and Cooper, 2017).* • Sourcing of renewables. • Sourcing of recyclable materials. • Secondary sources (recycled materials, Industrial Symbiosis, other cascades). • Restorative sourcing (Use former 'wastes' as input: Landfill re-mining or using ocean plastics). • Use of non-toxic or benign materials (to facilitate re-absorption in natural cycles). • Use the lowest suitable grade of materials suitable (Reserve the highest-quality resources for the most demanding task, and use used resources further down the chain). **Manufacturing** *Improve circularity potential and process efficiency in product manufacture through consuming fewer natural resources or energy, aim for 'gentani' (the absolute minimum input required to run a process) (Potting et al., 2017).* • Lean manufacturing & cleaner production (use less energy and materials, treat wastes, etc). • Rework (pre-user refurbishment or remanufacture). • Recycle (pre-user recycling). • Cascade (find uses for manufacturing waste: internally/ at other facilities (Industrial Symbiosis)). • Recover (energy recovery, or recovery of biological nutrients). **Product use & operation** *Improve circularity potential and efficiency in product use and operation through wiser use and operation of products (usually enabled by digital technologies), and aim for 'gentani' (the absolute minimum input required to run a process) (Potting et al., 2017; Reike et al., 2018).* • Enable product longevity through high product integrity and robustness. • Use idle product capacity (historical usage data can be used for improvements such as better scheduling (of downtime), and (give insight into the possibilities for) pooled or shared use). • Low consumables of energy, water and materials during product use and operation. ***Logistics*** *Improve process efficiency in logistics operations, aim for 'gentani' (minimum input into a process (Greenbiz, 2014)* • Combine forward & return logistics. • Incentivize eco-friendly driving and transport. • Minimize, reuse or recycle (transit) packaging. ***Energy***

		Improve energy efficiency and use clean(er) sources of energy (Cullen, 2017; Mestre and Cooper, 2017).
		• Use less energy • Renewable energy

Strategies included in the Circular Strategies Scanner *(cont).*		
Driver	**Strategy**	**Area of application or sub category** **Recirculation strategy** & synonyms ***Definition*** *(specifics)* • **Example practice(s)/ specifics**
Extend existing use cycles with the purpose of capturing (residual) value or to reduce value loss from continued use of parts and products	**Recirculate**	**Parts & products**
		Upgrade – Update, modernize, renew, retrofit, rebuild, overhaul, revive.
		Extend existing use cycle by adding value or enhancing the function of a product in respect to previous versions (Parkinson and Thompson, 2003; Potting et al., 2017).
		• Aesthetic upgrades (i.e. changing the coat or sleeve of a product due to a new preference). • Functional upgrades (i.e. software upgrades, hardware upgrades).
		Repair & maintenance – Corrective, condition based, predictive and prescriptive maintenance
		Extend existing use cycle by countering wear and tear, and correcting faulty components of a defective product/part to return it to its original functionality. ((Partial) disassembly envisioned, limited warranty may be issued). (Thierry et al, 1995; Stahel, 2006).
		• Providing a product with a service, which may involve the lubrication of critical parts, checking fasteners, the tension of chains and cables, the replacement of worn-out parts, etc. • Repair may involve the restoration or replacement of faulty parts and components.
Extend to new use cycles with the purpose of capturing (residual) value or to reduce value loss from continued use of parts and products.		Reuse – As-is reuse, redistribution, product cascading, minimise.
		Extend to new use cycle by reusing a part/ product (discarded/ not in use) that is still in good condition and can fulfil its original function in a different use context (new customer/user). (May involve a minimum amount of condition monitoring such as cleaning or repackaging. No warranties are provided and no disassembly is involved.) (Saavedra et al., 2013)
		• Selling used goods on platforms such as E-bay, • Return and resale of second hand goods through stores, such as Patagonia and Bergans. • The xStorage Home system (by Nissan and Eaton) gives old lithium-ion batteries from Nissan Leaf a second life inside of homes and businesses as backup and solar storage batteries.
		Refurbish – Recondition, retrofit, refresh, remodel.
		Extend to new use cycles by returning a part/ product (discarded/ not in use) to a satisfactory working condition that may be inferior to the original specification. (This may involve: cleaning, repairing, resurfacing, repainting, re-sleeving. Partial disassembly envisioned. In the case of traditional product sales, a warranty for all major parts may be issued (less than the newly manufactured equivalent)). (Ijomah, 2002, 2009; Saavedra et al., 2013).*
		• For example: taking in relatively modern, but disused white goods and performing repairs and/ or replacing lost parts and finding new users for the refurbished products (e.g. Norsk Omburk).
		Remanufacture – Rebuild, overhaul, remake.
		Extend to new use cycles by returning a product (discarded/ not in use) to at least Original Equipment Manufacturer (OEM) performance specification and quality. (Usually more rigorous and costly than refurbishment and involves total disassembly and reassembly. In the case of traditional product sales, a warranty that is at least equal to that of a newly manufactured equivalent may be issued). (Ijomah, 2002, 2009; Saavedra et al., 2013).
		• Renault engine blocks
		Repurpose – Alternate use.
		Extend to new use cycles by using a product (discarded/not in use) or its parts for different functions (Potting et al., 2017; Reike et al., 2018).
		• Mærsk providing containers to fit housing purposes in Copenhagen Village. • Using product packaging as storage or glassware (Nutella, Douwe Egberts).
Effective application in end-of-life of materials with the purpose of capturing (residual) value or to reduce value loss from continued use of materials.	**Recirculate**	**Materials**
		Recycle
		Extend material lifespan by processing them in order to obtain the same or comparable quality (Allwood et al., 2011).
		• Can-to-can recycling in beverage cans. • Chemical recycling of nylon.
		Cascade – Downcycling, upcycling.
		A subsequent use that significantly transforms the chemical or physical nature of the material (Sirkin and Ten Houten, 1994).
		• Repurposing of used clothing as an insulation material. • Used coffee grounds from coffee shops processed into biofuel, as medium for cultivation of edible mushrooms, for use in beauty products, etc.
		Recover
		Recover energy or nutrients from composting or processing materials. (Reike et al., 2018).
		• Incineration, pyrolysis or anaerobic digestion (recovery of energy). • Composting (recovery of biological nutrients).

Table 2 - Overview of the definitions of the circular strategies as used in the Circular Strategies Scanner.

8. Discussion

The Circular Strategies Scanner illustrates how to support visioning in COI processes, through supporting the explication of CE, mapping current CE initiatives, and generating ideas for increased circularity. With this, the framework of Potting et al. (2017) was significantly improved upon for the manufacturing context, see Table 3.

Criteria **The new framework should:**	**Potting et al. (2017)**	**Circular Strategies Scanner - v2.0**	**Summary of improvements that were realised**
01) A tool for inspiring, motivating and aligning people.	++	+++	*Improved capacity to serve as a boundary object where stakeholders can clearly identify their (influence on) activities, and see the applicability and relevance of circular strategies (see also the criteria below).*
02a) Balance the generation of new ideas, with that of describing existing situation.	++	+++	*The Scanner can directly and without transformations be used as a tool for mapping the circular strategies that are present in a situation, as well as for exploring what strategies can be improved or added (see section 6).*
02b) Provide an overview of the spectrum of available strategies ranging from incremental to transformative.	++	+++	*The Scanner groups circular strategies according to their potential for change in circularity levels. Strategies that can be thought of as having potential for incremental change are grouped under* Restore, reduce & avoid*; strategies that aim for higher levels of circularity through business model innovation are grouped in* Rethink & reconfigure*; and strategies that radically transform both business and user practices and achieve radical decoupling are placed in* Reinvent*.*
03) Indicate which strategies affect which business processes and related capabilities.	+	++	*The circular strategies in the Scanner are organised according to the business processes they apply to.* Reinvent *and* Rethink & reconfigure *represent groups that affect business strategy, and the remaining groups respectively affect operational processes, ranging from raw materials and sourcing, manufacturing, product use and operation, to the recirculation of parts and products, and materials.*
04a) Explicitly include the reduction and avoidance of resource use and impacts, as well as resource productivity strategies aimed at continued use and value delivery.	++	+++	*The Scanner covers a wider range of circular strategies, giving a more comprehensive overview of circular strategies that aim for the reduction and avoidance of resource use and impacts, as well as those that improve resource productivity strategies.*
04b) Allow for generating insight into circular configurations.	++	+++	*The Scanner implements a means of systematically exploring connections between circular strategies, through organising them in three 'levels' that indicate their relationship. This relationship can be bi-directional: e.g. a change in circular strategies in* Restore, reduce & avoid *may impact the circular strategies in* Recirculate and vice-versa*; or it may may be a unidirectional relationship where a change in* Reinvent *requires the reexamination of the relevance of circular strategies in* Rethink & reconfigure*, or where a change in* Rethink & reconfigure *requires a reconsideration of the strategies applied in* Restore, reduce & avoid.
05) Has to point to the value drivers that circular strategies can contribute to.	++	+++	*Each group of circular strategies in the Scanner is clearly linked to a value driver that aids its users in identifying relevant contributions to value creation and capture, such as improved efficiencies, supporting optimal use during the use phase, and value recovery opportunities, pointing to opportunities for either financial or non-financial gains within or outside the company.*
+++ = framework satisfies criterion very strongly, ++ = framework satisfies criterion strongly, + = framework satisfies criterion moderately, 0 = framework doesn't meet criterion or only marginally.			

Table 3 - Overview of the the improvements that the new framework makes in relation to the framework by Potting et al. (2017) that was used as a basis for its development.

A strength of using the Scanner in COI is that it provides a way of systematically exploring circular strategies. It thus provides guidance in identifying what business areas eco-innovation for CE is possible or necessary. For instance, when improved recycling is identified as an opportunity, the Scanner indicates that other circular strategies in the operational areas of raw materials and sourcing, manufacturing, product use and operation, and the recirculation of parts and products may be affected. Such impacts may be synergistic and result in increased overall circularity (e.g. the choice to change to a recyclable material to enable end-of-life recycling also enables recycling of waste within the manufacturing process), or they may take the form of trade-offs and require additional management or development for resolving them (e.g. changing to a recyclable material negatively affects the technical longevity of a product). Further work could focus on providing additional guidance with regards to how to systematically identify synergies and trade-offs.

Application of the Scanner furthermore strengthens the connection between eco-innovation and CE, by linking it with transformative innovation (De Jesus et al. 2018). It does this in two ways in COI processes. First, due to possibilities uncovered in the operational area, it can trigger a re-evaluation of the value generation architecture. Second, when the value generation architecture is the starting point, the Scanner indicates that the role of the circular strategies on the operational level need to be revisited as their relevance may increase or diminish depending on the context. In both cases, the Scanner invites a reconsideration of the system the manufacturing company is attempting to transform and links circular strategies together in circular configurations: situations where two or more circular strategies work together (Blomsma et al., 2018).

The range of sectors used for the validation efforts - heavy machinery, electronics and furniture - points to the broad applicability of the Scanner for manufacturing companies from different sectors. However, the framework could be further strengthened by validation with a wider set of manufacturing companies, including those that (also) operate within the biocycle, or that provide dissipative products (e.g. paints, lubricants, cleaning agents and other chemicals).

Further work should address how the Scanner can be linked to the assessment of (combinations of) circular strategies and different implementation scenarios, such that in the early stages of innovation processes the impact on economic, environmental and social systems can be evaluated and actions implemented to minimise negative impact and maximise positive impact. It could furthermore be explored whether the framework has potential to address the lack of a common understanding between value chain actors, which is perceived as an obstacle for the implementation of CE (Machacek et al. 2017; Lapko et al. 2018). In addition to using the Scanner by itself, there is also a need for understanding how different classes of circular strategies frameworks (e.g. macro, meso, micro, nano, networked) can best be used together.

9. Summary and conclusion

With this paper, we have contributed to the development of support tools for CE oriented innovation, or COI and to enable the translation of the CE concept in practice by creating support for visioning for CE. The contribution of this paper is four-fold: a) it provides an example of a process of how a circular strategies framework can be developed for a specific business type with the ability to support COI processes, b) it proposes a circular strategies framework for the manufacturing context, with c) an accompanying set of definitions of circular strategies, and d) it provides an example of how such a framework can be used in the early stages of a COI process. Next, it will be discussed how each goal was achieved and what the implications are for academia and industry.

In support of the first goal - to provide an example of the development of a circular strategies framework - this paper used the lens of Design Research Methodology (Blessing and Chakrabarti, 2009). This answered the call for the more deliberate and systematic development of circular strategies frameworks that are fit for purpose, voiced in Niero and Hauschild (2017) and Blomsma (2018). With manufacturing companies as the focus, it provided an example of how academia and industry can work together following a transdisciplinary approach (Sakao and Brambila, 2018) in developing resonant frameworks for specific audiences. The systematic development approach followed in this paper can be adapted and further expanded upon for other business types or other innovation contexts.

The second goal was achieved through the provision of the Circular Strategies Scanner. This framework can be used as a tool in COI and provides practitioners in manufacturing with a way of contextualising the CE concept, mapping current CE initiatives, and generating ideas for increased circularity. The third contribution, the set of circular strategies definitions included in the framework, served to support the consolidation of CE terminology and bringing academic and practitioner terminology closer together (Reike et al. 2018; Meste and

Cooper 2017; Kalmykova et al., 2018). This was achieved through drawing on both academic and practitioner perspectives with regards to these definitions in the development process. Together, these two points mean that an important iteration on the framework provided by Potting and colleagues was made, which brings more precision to the framework and which customises it for the manufacturing context. With this, the framework has been transformed from analytical framework into an innovation tool.

The fourth goal was achieved through illustrating how the Circular Strategies Scanner can be used in the early stages of a COI process to create a shared vision. The examples provided are of its application within businesses (see section 6). As well as with these companies, the Scanner was used with the other manufacturing companies participating in the CIRCit project. Specifically, it was used in the early stages of the action research, which allowed for a clear vision to be developed and establishing a clear direction for the work that followed, as it clarified with what aim different business activities relevant for COI needed to be deployed, whether this involved sustainability assessment, business model innovation, product design, digital technology strategies, the creation of take-back systems or value chain design.

Equally the Scanner could be applied across businesses, but also between business and academia, and beyond. In these contexts, the Scanner can serve as a boundary object where the stakeholders can clearly identify their activities or influence on different business processes across the life cycle, also enabling the comparison of CE initiatives and sharing of best practices.

Acknowledgements
This article is one of the outcomes of the research project CIRCit (Circular Economy Integration in the Nordic Industry for Enhanced Sustainability and Competitiveness), which is part of the Nordic Green Growth Research and Innovation Programme (grant numbers: 83144) and funded by NordForsk, Nordic Energy Research, and Nordic Innovation. We would also like to thank the companies participating in the CIRCit project and the anonymous reviewers whose thoughtful feedback aided the development of this work.

Appendix A

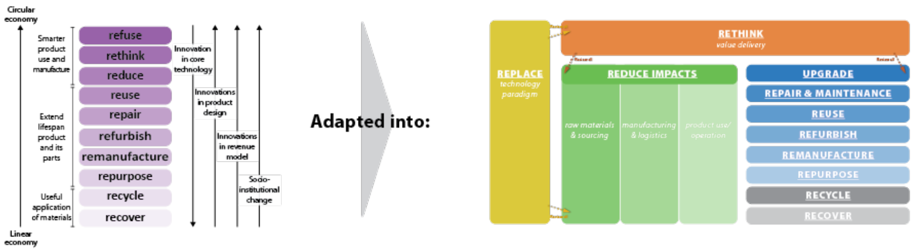
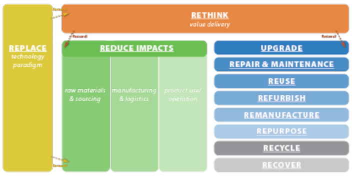
Overview of changes to adapt the Potting et al (2017) framework for the manufacturing context		
		
Major adaptations - changes in the structure of the framework		
#	In Potting et al (2017):	First version of Circular Strategies Scanner:
1	Circular strategies organised hierarchically: ranging from those that are considered more linear to those that are increasingly more circular.	Circular strategies are organised according to the business functions they apply to, in five main areas: *Replace*, *Rethink*, *Reduce Impacts* and two other operational process areas respectively containing end-of-use and end-of-life strategies
2	'Reduce' presented a single high-level strategy.	Specified into 'Reduce impacts' and the sub-categories of 'raw materials & sourcing,' 'manufacturing & logistics,' and 'product use/ operation.'
3	-	A visual structure consisting of three levels has been created to indicate the relationship of circular strategies, through the relative placement of the boxes containing the strategies, and the addition of arrows.
Medium adaptations - changes to the sub-groups or categories of the framework		
1	Inclusion of *Refuse* at the top of the hierarchy.	In the Circular Strategies Scanner, this strategy is understood as consisting of two sub-strategies and it was therefore split in two: *Refuse* (to abandon a practice altogether) and *Replace* (see Table 2). *Refuse* was subsequently not included in the framework, due to this framework targeting companies (see also Discussion section).
2	Contains the value driver: "Smarter product use and manufacture" for *Refuse*, *Rethink* and *Reduce*.	To refine this further, this value driver was split into "dematerialise/ combine functions" for *Replace*, "function & value proposition to market" for *Rethink*, and "improve circularity potential and efficiency" for *Reduce Impacts*.
3	Contains the value driver: "Extend lifespan of products and parts" for *Reuse*, *Repair*, *Refurbish*, *Remanufacture* and *Repurpose*.	To refine this further, this value driver was split in two to align with the end-of-use and end-of-life groupings as in line with Potting. As a result, *Upgrade*, *Repair & Maintenance* and *Reuse* are assigned the driver "Extending existing use-cycle," and *Refurbish*, *Remanufacture* and *Repurpose* are assigned the driver "Extending to new use-cycle."
Minor adaptations -- refinements in labels, definitions and the order of circular strategies		
1	Inclusion of *Recover*, as a strategy that refers to energy recovery through incineration, anaerobic digestion, pyrolysis.	The definition of *Recover* has been expanded to also include the recovery of biological nutrients and as such also covers such strategies as composting.
2	-	*Upgrade* was added to the framework to make explicit evolving quality and performance requirements of products.
3	*Reuse* comes before *Repair* in strategy order.	The order of *Reuse* and *Repair* was reversed, as Reuse that involves mere redistribution of products will – theoretically – maintain value to a higher degree with less added investment of resources, than redistribution that is also combined with repair activities.
4	Includes *Repair* as a circular strategy.	Repair was extended to also include maintenance, which is a common terminology in companies, and as such is indicated as *Repair & Maintenance* in the framework.

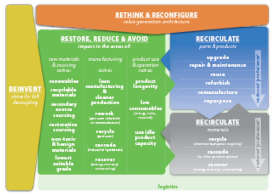
Table - This overview explains which changes were made to the Potting et al (2017) framework in order to adapt it to the manufacturing context. It gives a complete overview of the major, medium and minor adaptations.

Appendix B

Overview of changes to refine the 1st version of Circular Strategies Scanner and develop the 2nd version



Further refined into:



Medium adaptations - changes to the sub-groups or categories of the framework		
#	First version of framework	Second version of Circular Strategies Scanner:
1	The process of *Logistics* featured alongside *Manufacturing*.	*Logistics* is assigned a separate area in the framework, to better reflect that it covers all the operational process areas.
2	-	*Energy* was added as a relevant layer. That is: circular strategies should be considered with the intent to reduce overall energy consumption, and use clean(er) and renewable sources wherever possible.
3	Featured the strategy *Reduce Impacts*.	Label of strategy was changed to *Restore, Reduce and Avoid* to more fully reflect the range of strategies relevant for raw materials and sourcing, manufacturing and product use and operation.
4		Explicit addition of relevant strategies in *Restore, Reduce & Avoid.* Such as restorative sourcing (i.e. re-mining from landfill or using ocean plastics), lean and cleaner production practices and using idle product capacity. *Cascade* was also included: it can occur as Industrial Symbiosis and either as a secondary source sourcing strategy, or as a way of managing the co- and byproducts from manufacturing.
5	No detail provided regarding Rethink & Reconfigure.	To clarify the framework's relationship business models aspects, detail was added to the Rethink & Reconfigure category. This was done by drawing on Bocken et al. (2016) and Tukker's (2004) and adding the four main categories of Multi-flow offering, Long-life products, Access or availability, and Result and performance.
6	No explicit place for product and process design.	Product and process design are explicitly acknowledged by including them as box between Rethink & Reconfigure and the operational process of Restore, Reduce & Avoid and the Recirculate parts, products & materials.
Minor adaptations - refinements in labels, definitions and the order of circular strategies		
1	Value drivers largely based on Potting et al. (2019).	Value drivers were further refined: for *Reinvent* it was changed to "strive for radical decoupling," and for *Rethink* to "aim for business innovation for circularity," and for *Restore, Reduce and Avoid,* to "prevent excess, improve efficiency and aim for 'gentani' and improve circularity potential."
2	Visual structure consisting of three levels has been created to indicate the relationship of circular strategies, through the relative placement of the boxes, and the addition of arrows.	Visual layering emphasised through depicting it using the visual metaphor of physical layers, which takes the form of drop shadows and arrows to indicate the relationship between the process areas. Hierarchical relationships indicated by a single arrow, trade-offs and synergies by bi-directional arrows.
3	No indication of hierarchy of end-of-use and end-of-life strategies	Arrows were added to indicate the (theoretically) preferred application order of these strategies.
4	Headings only applied for *Replace, Rethink* and *Reduce Impacts.*	For consistency, all five process areas are given headings. End-of-use processes are titled *Recirculate – parts & products* and end-of-life processes are titled *Recirculate – materials*.
5	-	*Cascade* was added to *Recirculate – materials*. This adds the distinction between recycling – i.e. those processes that keep material circulating at or near virgin levels of performance, and cascades – i.e. those processes that extend the life of materials through allowing for reduction or redefinition of performance characteristics.
6		Addition of descriptors to strategies to aid in clarifying the type of application. For example: recycling can take place at the manufacturing stage, where it involves re-entering waste from the manufacturing process back into the process: pre-user recycling. It can also take place post-user at the *Recirculate – materials* stage, in the form of chemical or physical (mechanical) recycling.
7	Featured the strategy label *Replace*.	*Replace* was changed to *Reinvent - strive for full decoupling*, to prevent confusion in relation the replacing harmful chemicals with less harmful or benign ones. Moreover, this term better conveys the transformative nature of this strategy.
8	Featured the strategy label *Rethink value delivery.*	Changed to *Rethink & Reconfigure value generation architecture.*

Table - This overview explains which changes were made to the first version of the framework in order to develop the second and final version. It gives a complete overview of the medium and minor adaptations. No major adaptations were made at this stage.

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sustainability

Article

Visualization and Interpretation of Life Cycle Sustainability Assessment—Existing Tools and Future Development

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Abstract: The aim of this study is the evaluation of Life Cycle Sustainability Assessment (LCSA) visualizations, which have been gaining increasing relevance in recent years. Despite this, the final interpretation and visualization of LCSA are not yet sufficiently established. Three of the existing LCSA visualization tools, Life Cycle Sustainability Triangle (LCST), Life Cycle Sustainability Dashboard (LCSD), and Sustainability Crowns, are compared and discussed along previously established target criteria. Subsequently, a "new" visualization tool (LCSA-Wheel) is developed based on analysis results and tested within a case study. It became clear that the LCST and Sustainability Crowns are mainly used to help weigh the sustainability dimensions. Nevertheless, the Sustainability Crowns meet most of the defined target criteria and thus serve as a model for the development of a visualization approach. The LCSD maps a wealth of information but is more difficult to understand without a deeper dive into the topic. The proposed LCSA-Wheel adopts a clear structure and provides information needed to understand the visualization. Although further developments are still necessary for general applicability, there is a justified assumption, shown with the help of a case study, that the LCSA-Wheel will gain acceptance in science and practice and thus drive the use of the LCSA.

Keywords: life cycle sustainability assessment; visualization; interpretation; wheel; dashboard; triangle

Citation: Backes, J.G.; Steinberg, L.S.; Weniger, A.; Traverso, M. Visualization and Interpretation of Life Cycle Sustainability Assessment—Existing Tools and Future Development. *Sustainability* **2023**, *15*, 10658. https://doi.org/10.3390/su151310658

Academic Editors: Roberto Giordano and Monica Lavagna

Received: 31 May 2023
Revised: 29 June 2023
Accepted: 4 July 2023
Published: 6 July 2023

1. Introduction

The issue of sustainability is becoming increasingly important in all areas of human life, especially due to the ongoing climate change. The earth and its atmosphere are warming up, environmental disasters are occurring more frequently, and species extinction in the animal world is increasing—these and many other consequences of climate change are urging people to live more sustainably and considerately. Two aspects of sustainability that, along with environmental sustainability, came into general awareness later and are still partly neglected are economic and social sustainability [1–3]. All three aspects are considered in the Life Cycle Sustainability Assessment (LCSA) framework—also to evaluate the overall sustainability with a view to climate change. LCSA assesses product performance in terms of environmental, economic, and social sustainability [4–6]; is gaining importance in academia and also in industry and is being increasingly used and developed [7]. Examples of recent applications of the LCSA framework in construction are the studies by Raymond et al., Balasbaneh and Marsono, and Touceda et al. [8–10].

However, some challenges, such as standardization and unification, interpretation, and visualization still need to be addressed for the daily practice of LCSA. Furthermore, to achieve a wider application of the LCSA framework in product and process development, i.e., especially in practice, the introduction of simplified tools and aids for interpretation and visualization is needed [2,7]. Valdivia et al. described in their research paper about the principles for the application of life cycle sustainability assessment, that one of the major issues with LCSA is an inconsistent application and a lack of transparency with the underlying data and assumptions made. To ensure this, the authors elaborated 10 principles for conducting an LCSA study, which also includes a transparent communication of the three pillars of sustainability [3]. The aim of this publication is to address the interpretation and especially the visualization of the LCSA. Assessment and visualization tools already introduced by other authors are presented. They are methodically compared and critically discussed based on developed target criteria. Finally, based on the established target criteria and the elaborated strengths and weaknesses of the existing visualization approaches, a further proposal for a visual, flexible-adaptable tool for the interpretation and presentation of LCSA results is elaborated. The created tool is critically discussed and necessary further developments are presented. The target audience of this publication is LCSA users and experts, but also laypersons and people generally interested in sustainability (assessment) and visualization should be addressed—regardless of the sector.

2. State-of-the-Art in LCSA Visualization

Kloepffer introduced the first of two main formulations for the LCSA [5,6,11]. In terms of content, due to general acceptance, it is based on the three-pillar model, which was already introduced in 1987 by the German Oeko-Institut [6,12]. This states that in order to achieve or evaluate sustainability, the environmental, economic, and social aspects must be aligned and reviewed [4–6]. Based on this, Kloepffer [6] and Finkbeiner [5] developed the following formal equation for the sustainability assessment of an entire life cycle (1):

$$\mathrm{LCSA} = \mathrm{LCA} + \mathrm{LCC} + \text{S-LCA} \tag{1}$$

LCSA = Life Cycle Sustainability Assessment
LCA = (Environmental) Life Cycle Assessment
LCC = Life Cycle Costing
S-LCA = Social Life Cycle Assessment.

In this framework, the LCA is defined as a standardized environmental life cycle assessment. The LCC is anchored as a life cycle costing assessment similar to LCA, while the S-LCA is the social life cycle assessment.

The second main formulation of LCSA by Guinee et al. defines LCSA as a transdisciplinary integration framework of models rather than a single model [1,11]. The framework is also based on the three sustainability dimensions but expands the focus from predominantly product-related content to sectoral and whole economy levels [1].

The LCSA has been used increasingly since 2008/2010. With growing interest on the part of experts and laymen, the topic of LCSA interpretation and visualization is also increasingly coming into focus. At this point, there are already five approaches to LCSA visualization and interpretation, which are presented in the following. In the further course of the publication, we focus on the first three presented visualization tools (Life Cycle Sustainability Dashboard, Sustainability Crowns, and Life Cycle Sustainability Triangle) as groundwork for future development. This selection was made according to their relevance and application to other research papers.

2.1. Life Cycle Sustainability Dashboard

The Life Cycle Sustainability Dashboard (LCSD) is a mathematical and graphical application to present the results of LCSA by an overall index and visualized by a dashboard with color scales, initially developed in 1998 as a Dashboard of Sustainability (DoS). The tool is designed to trace the influences of three sustainable pillars which match the environmental, economic, and social dimensions examined in LCSA. It is a tool that uses the main indicators used in LCSA and specific aggregation for the synthetic representation of the different sustainable development dimensions [4,13–16].

The first version of DoS aimed to evaluate and compare the status and progress of all nations regarding their performances in sustainability [4]. The dashboard was a possibility to share the results in an easily comprehensible way with the public and media. Already the DoS had the function to influence the public debate, support decision-makers, and help to rethink the strategies of governments, agencies, or development banks [13]. The application has been modified to assess complex data not only for countries and communities anymore but to extend it for districts and cities on the one hand and the other hand to apply it also for products, services, and organizations [15,17].

The LCSD is a possibility to put the results of LCSA into a visualization that helps to understand the complexity of the high amount of diversity and indicators and to break the barrier between LCSA experts and non-experts who are both involved in a decision-making process [18]. To simplify this visualization process, it is indispensable to improve the communicability of the data which LCSD does through its visual presentation. The visualization makes it easier to interpret the results, provides a comprehensible picture of the aspects compared in LCSA, and ejects the positive and negative impacts of the assessment [13,17].

The visualization is designed as a dashboard. This dashboard possesses two essential characteristics that make the tool stand out: First, the possibility of comparison between multiple aspects in their economic, environmental, and social dimensions. The indicators are possible to consider separately for each dimension but also aggregated by an overall index. Second, the graphical illustration of the assessment and the comparison of the results are presented by a chromatic scale and a ranking score [4].

It is optional to create an individual dashboard in which the topics and the indicators are free to choose and customize. Consequently, the set of indicators used for an LCSA is easily implemented in the LCSD macro. The tool can be used only for comparing more scenarios. If it is wished to compare more scenarios, one needs to define at least one reference scenario and compare the questioned one against it [5]. If the tool is used for comparison, there are different levels on which the different products or scenarios are compared with each other. These include the indicator level, the topic level, and the aggregated Sustainability Performance Index. The worst performance is assigned a value of 0 while the best performance is assigned a value of 1000. Performances in between are calculated by linear interpolation [4,18]. The ranking score is not only applicable to the indicators but again to all levels. The overall sustainability performance index is calculated by taking the arithmetic mean of all topic scores [18]. This index is called the overall policy performance index (PPI) [15].

As an additional feature of LCSD a weighing of the indicators is possible. This feature is an important tool to demonstrate a realistic evaluation scheme as weighting happens unconsciously in every decision-making process. However, it is a critical tool as it can lead to propagandistic and therefore falsified results [4]; further, weighting is discussed in the LCSA context [3].

The most important part of communicability and an understanding of the contributions of the overall performances is the visualization of the results. In LCSD a chromatic scale and a colored ranking score fulfill this task [18,19]. The performances of each indicator are transposed into colors. The medium performance of an indicator is expressed by the color yellow. Every performance in between is similar to the interpolation of the values scaled in shadings between the colors of the extremes (green and red) [17,18].

The color scale and the familiar image of a dashboard with a needle showing the overall result is the main advantage of this visualization tool. Further positive aspects of the LCSD are the two options of illustration, the visual presentation on one hand but also the availability of a detailed numerical database on the other hand [18]. The results of the LCSD can give a summarized picture of complex data and can identify trends that facilitate any decision-making process. The ranking score and the color scale enable all stakeholders involved to interpret and understand the results easier as the dashboard can picture a solution or an approach toward more sustainable choices.

2.2. *Sustainability Crowns*

The Sustainability Crowns by Corona and San Miguel [20] form a circle that presents one alternative that is taken into consideration for the decision-making process. Compared to the LCSD, the Sustainability Crowns do not provide any weighting of the indicators or the dimensions. The inventors avoided including weighting intentionally as it depends on subjective values, and it could lead to an information leak. For the same reasons, they are cautious about aggregation, which is why, in contrast to the LCSD, no overall score per alternative is presented or calculated. Thus, the performance of an indicator is assessed according to the average of that indicator's performance within the alternative values. The percentage deviation to the average value then indicates the color shown in the circle (Figure 1). According to Corona and San Miguel, the Sustainability Crowns are more flexible than the LCSD because they offer more options for listing different criteria. A lack of further literature as well as broad applications are noticeable for the Sustainability Crowns.

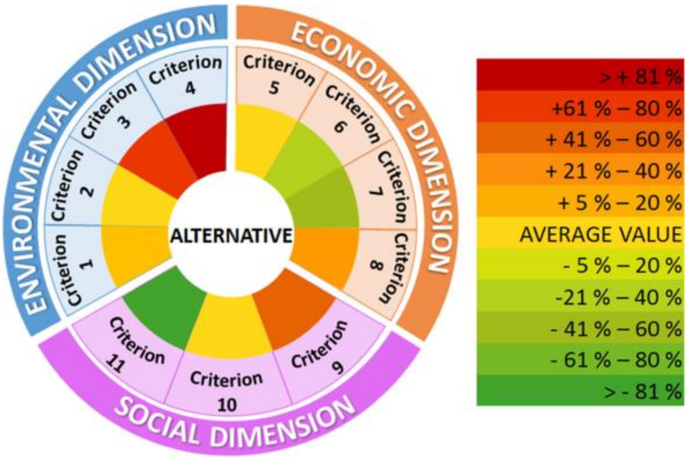

Figure 1. Sustainability Crowns by Corona & San Miguel [20].

2.3. Triangles

The shape of a triangle is an intuitive choice for the visualization of three categories, as there are always three corners that can represent each of the categories, such as the sustainability dimensions. However, there are different realizations of a triangle as a visualization tool. With time, various models have emerged that are either partially based on each other, such as the 'posterior triangle' on the Life Cycle Sustainability Triangle (LCST) [21], or were developed independently from each other.

2.3.1. Life Cycle Sustainability Triangle

The LCST has its origin in the 'Mixing Triangle' which was first named and designed by Hofstetter et al. [22], and further developed by Finkbeiner et al. [5] for the application in conjunction with LCSA. Hofstetter et al. initially intended to design a triangle that considers three safeguard subjects regarding environmental impacts. However, the inventors also mention that the triangle can be applied to any three different parameters. Within the LCST it is possible to create a ranking of alternatives and to figure out the different strengths within the alternatives regarding the three dimensions. The visualization tool aims to illustrate the results of LCSA for all possible weighting sets to have an overview of the performances of the alternatives regarding the sustainability dimensions [22].

The choice of the corner for each dimension is not relevant if there is a clear assignment and gradation of the sides of the triangle. A corner indicates that the requirements of one of the dimensions are met completely, while the requirements of the other two dimensions are not fulfilled at all [5,22]. Each side of the triangle is divided into ten sections as the weighting factors of one dimension run in steps of ten. Therefore, the overall triangle is separated into many small triangles. Every corner of one single small triangle represents one possible weighting set of the three dimensions (Figure 2). For the evaluation, the performance values calculated with LCSA are normalized in one dimension for each alternative and then multiplied by the chosen weighting factors. Afterward, they are added up to one index which is called eco-index (EI), and calculated as follows (2):

$$EI = W_E \times P_E + W_{Ec} \times P_{Ec} + W_S \times P_S \quad (2)$$

P: performance value of one alternative for each dimension (E = environmental, Ec = economic, S = Social)

W: the weighting factors of one reference point in the triangle which always need to be positive and add up to 100% (E = environmental, Ec = economic, S = Social).

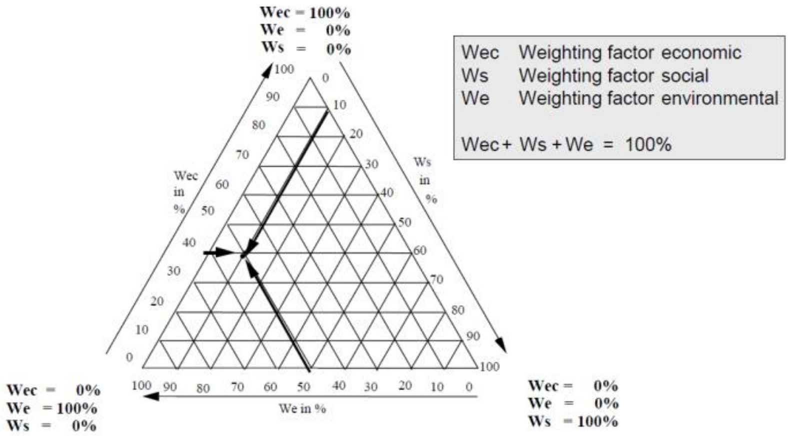

Figure 2. LCST according to Finkbeiner et al. [5].

2.3.2. A Posterior Triangle/PS(S)M

The posterior triangle is based on the LCST and was designed by Müller and Hiete [21] for companies, and provides an overview of the performances of all alternatives for every possible weighting of the three dimensions of sustainability. This model is intended to ensure that no a priori weighting or aggregation takes place. The significance and meaningfulness of the individual weighting combinations are determined by the decision maker. Such as in LCST, the posterior triangle mainly represents the superior alternative.

A requirement for the application of the triangle is data from a full LCSA which has to be normalized and aggregated into the three sustainability dimensions. Both aggregated sustainability data and ready-to-use database data are suitable for implementation for the visualization. The preparatory work until the final visualization is considered to be very time-consuming, and both labor and data-intensive—as often in LCSA. Advanced knowledge in the field of sustainability assessment is required, while basic programming skills are sufficient. The normalization and aggregation can be realized in Microsoft Excel in which the LCSA data can be imported easily. The visualization steps have been performed with MATLAB, but also programming languages such as Python can be used as alternatives. It is recommended that the decision-makers make use of the Distance-to-Target (DtT) normalization which is applied for each sustainability dimension. DtT normalization aims to align the assessed performance with a desired target. For the normalization of the indicators of each sustainability dimension, an external weighting is used to make sure that the middle of the triangle represents an equilibrium of all three dimensions, so no rank reversal issue emerges. In the end, it is a compensatory approach as the aggregated sustainability score portrays the weighted sum of all sustainability dimensions' performances.

Similar to the LCST, the evaluation approach offers an overview of all possible weighting combinations of all three sustainability dimensions. In contrast to the LCST, however, a posterior triangle works with colors. According to Müller and Hiete [21] the posterior triangle is not applicable for more alternatives than three: which is why they created an additional visualization method that has an unlimited capacity of alternatives that can be assessed—the product selection map (PSM).

The posterior triangle underlines the influence of different weighting combinations, as it avoids the "winner-takes-all" approach. Stakeholders can consider different sustainability performances and gain a deeper understanding of the results through different visualization options. Decision makers can take management relevant criteria into account and a posterior weighting enables multi-objective decision-making. In general, subjectivity is a much-discussed factor that cannot be avoided in evaluation approaches as a basis for decision-making processes. As soon as aggregation and weighting are involved, subjectivity automatically plays a role in the assessment. This uncertainty needs further research but was not addressed in the study of Müller and Hiete [21] (Figure 3).

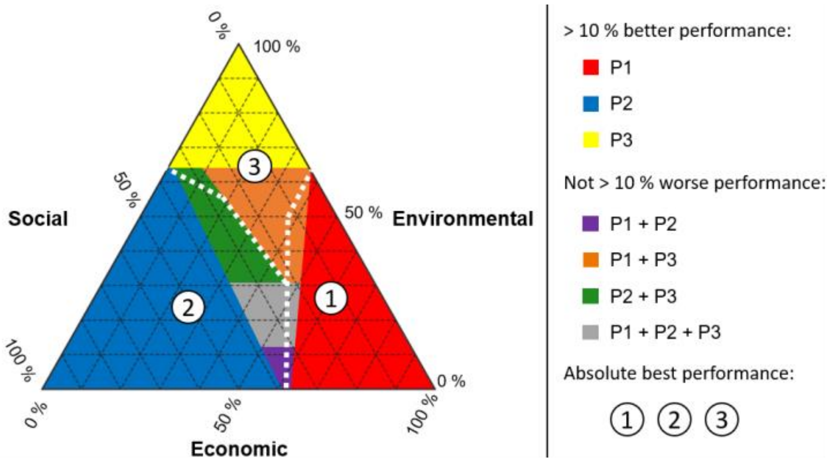

Figure 3. A posteriori triangle according to Müller & Hiete [21].

2.3.3. Three-Sided Triangle

Another visualization approach using the shape of a triangle has been developed independently in two different papers—both use the same concept of visualization. While Omran et al. [23] follow the LCSA results and use the three sustainability dimensions as the three corners of the triangle (see Figure 4), Penn and Fields [24] invoke the triple bottom line created by John Elkington which include the factors people, profit, and planet. These are easily transferable to the three sustainability dimensions. Instead of profit, Penn and Fields [24] use the alternative term price which does not make a difference to the evaluation.

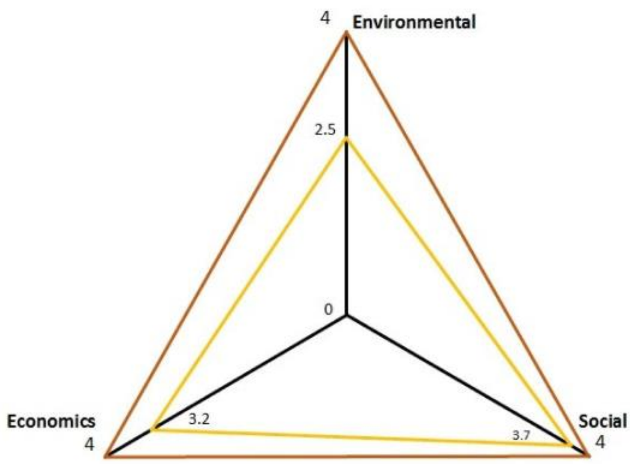

Figure 4. Three-sided triangle according to Omran et al. [23].

The three-sided triangle is intended to illustrate the relative balance between the sustainability dimensions and thus to identify the trend of the sustainability performance over time by regularly repeating this graphical assessment [23,24]. It is an effective approach to compare the broad picture of different alternatives and to identify the imbalances within the sustainability dimensions. For Penn and Fields [24] the visualization is primarily a tool useful to introduce the sustainability concept and the triple bottom line to students. For a more in-depth evaluation of LCSA or sustainability in general, studies and approaches from other sources need to be used and adopted [24]. Omran et al. use the triangular illustration for examining the sustainability of crude palm oil production in their study [23].

2.3.4. Integrative Triangle

The integrative triangle is an approach by Hauff and Kleine [25] to visualize the relationships between the three pillars of sustainability. The triangle itself is divided into several sections that describe the relationship between the fields of action and the indicators. While the dimensions can still be considered separately from each other, the areas inside the triangle serve to clarify the interrelationships of the dimensions and provide a multidimensional perspective. The more distant a field in the triangle is from the dimension's corner, the less connection there is to the dimension. The triangular field that lies directly at the corner of one dimension is exclusively classified into this respective dimension. A more distant field from a corner is still classified as mainly economic, social, or environmental, but already has influencing factors from other dimensions. The fields that touch both dimensions' triangles in one corner are equally linked to both dimensions [25].

3. Analysis of Existing Tools

In the following section, the focus is placed on three different forms of visualizations already presented: LCSD, LCST—as these are the most often named and cited ones in the LCSA-field. They are compared methodically, examined for strengths and weaknesses, and critically discussed.

3.1. Methodology

The methodological comparison procedure of the three named visualization tools is presented in the following. To ensure objectivity, the comparison of the existing visualization tools is carried out based on defined comparison criteria. For this purpose, general goals for the creation of a good visualization are first introduced in the following chapter. Subsequently, specific target criteria are developed on this basis, which should be fulfilled for the successful presentation of LCSA data.

Goals for the Creation of a Targeted Visualization

Schumann and Mueller [26] defined three generally applicable goals for creating a good visualization [26]. From all criteria reviewed within the existing literature, their approach was the most suitable for applicability within Life Cycle Sustainability Assessment. According to Schumann and Mueller, the visualization of data should fulfill the following goals: expressivity, effectiveness, and appropriateness. Expressivity is fulfilled when only the information contained in the data set is represented in the visualization. A visualization can thus be described as expressive if it depicts the considered data set in an unaltered way. The expressivity criterion can be fulfilled for a set of facts by different types of visualizations, which does not imply that these are effective. The effectiveness of a visualization tells how well the chosen form of representation reflects the data set. If the viewer can intuitively understand the information of a data set from a graphical representation, the effectiveness criterion according to Schumann and Mueller is fulfilled. The fulfillment of expressivity and effectiveness, in turn, do not indicate the appropriateness of a visualization. The appropriateness criterion is used to weigh the effort and costs involved in creating a graphical representation concerning its usefulness. Visualization can be expressive and effective but provides too little benefit to its effort. Thus, the visualization would not be appropriate [26]. Since this publication focuses on the graphical representation of LCSA, the three goals of a good visualization according to Schumann and Mueller are suitable as comparison criteria for the analysis of the already introduced visualization tools. In the following, the target criteria of expressivity, effectiveness, and appropriateness are explicitly adapted, elaborated, and explained for the LCSA framework and the presented tools.

Expressivity

Three criteria of expressivity should be met in the presentation of the LCSA:

(1) Mapping of an overall result for the LCSA.

Since visualization should establish itself as an application and interpretation approach in science and practice, a simple readability of the overall result of the LCSA is indispensable. This facilitates the use of the tool both for non-experts who, for example, want to compare two products based on the visualization when making a purchase decision, and for experts. In case a user prioritizes the result of a certain criterion or one of the sustainability dimensions in his/her weighting, the mapping of the LCSA result can be considered as additional information.

(2) Including and mapping the three pillars of LCSA.

The visualization should include and map the three pillars of the LCSA (LCA, LCC, and S-LCA). The three-dimensional view is necessary to consider the different priorities of all users. Particularly when looking at large organizations and companies, the relevance of mapping all three dimensions becomes clear. For example, a company to which profit is the highest priority would likely make decisions based on the best LCC score. An environmental organization, on the other hand, would possibly focus on the LCA outcome, while another organization would decide according to the S-LCA score.

(3) Information/reference to the basis of assessment.

Another essential aspect of the completeness of the visualization is a transparent presentation of the basis of the assessment. The results of the three pillars are determined based on the evaluation results of the associated criteria. To ensure the transparency of the results, these criteria and their evaluation results should be presented in some form. A detailed legend or a link to a database can be suitable for this purpose.

Effectiveness

The LCSA is a scientific framework that, supported by a suitable visualization, should be quickly understood and applied in practice by both experts and non-experts. Therefore, ensuring effectiveness is of particular relevance.

(1) Use of a color scale including a corresponding legend.

The use of a color scale including a corresponding legend facilitates the understanding of the visualization for the user. These can be used to classify results at first glance and thus serve to make the presentation comprehensible and to raise the interest of different users.

(2) Illustration of results.

Furthermore, the reporting of numerical results, both for LCSA itself as well as the sustainability dimensions and their evaluation criteria, is urgently needed in addition to the use of a color scale. The numerical results, even though it is one of the most challenging aspects, should be given either in relative (in comparison with reference/other scenarios) or absolute numerical values with an associated calculation explanation. For LCA a reference scenario or best-case scenario would present all values as zero; for S-LCA for example, a best-case scenario is more difficult to name.

(3) Quantity of the listed information to a suitable extent.

The quantity of the listed data is difficult to define as an objective evaluation criterion—which in general is an often-discussed topic in LCSA. Nevertheless, this is an important prerequisite for a good visualization: On the one hand, the presentation should not scare the user with a flood of information, and on the other hand, all important information should be included and easy to find and read.

Appropriateness

Even though LCSA is a framework that has gained relevance and attention in recent years, the effort and cost of visualizing LCSA results must be in proportion to the benefits. To ensure a high benefit of the visualization tool, the following criteria should be met.

(1) Global applicability of the visualization and its associated database.

The visualization and its associated database should be globally applicable, as data in LCSA often is expensive (paid software and database) or confidential (primary industry data) aspects. A necessary condition to achieve the goal of global applicability is the use of a standardized language.

(2) Simple adaptability for new developments.

The growing interest and the increasing number of publications in the subject area of the LCSA suggest a constant change, and a further development of the LCSA. New findings in the field of the LCSA must not lead to the fact that the visualization cannot be used at all or only by new development. Therefore, the flexible adaptability of the visualization tool is a necessary criterion. Adaptability could also imply the possibility to add new indicators to the LCSA visualization tool.

(3) Comprehensibility of the visualization.

The comprehensibility of visualization is difficult to formulate as an objectively assessable criterion. Nevertheless, the form of presentation used should be easy to understand and use, even for users who are not familiar with the subject matter. This ties into the issue of a common language/understanding, that still needs to be improved for LCSA [2,27].

3.2. Results

The results of the comparison are summarized in Table 1. The top column lists the three named visualization tools, with Sustainability Crowns abbreviated as 'Crowns'. The left columns list the nine comparison criteria.

Table 1. Fulfillment of the comparison criteria by the existing visualization approaches (legend: + = criterion is completely fulfilled; ± = criterion is partially fulfilled; − = criterion is not fulfilled)—reasoned (subjective) rating.

Visualization			LCST	LCSD	Crowns
1	Expressivity	Mapping of an overall result for the LCSA	−	+	−
2		Mapping the three pillars of the LCSA	−	+	±
3		Information or at least a reference to the basis of assessment	−	±	±
4	Effectiveness	Use of a color scale including a corresponding legend	−	+	+
5		Illustration of numerical results (relative or absolute)	−	±	±
6		Quantity of the listed information to suitable extent	+	±	+
7	Appropriateness	Global applicability of the visualization and its associated data basis	+	+	+
8		Simple adaptability for new developments	±	+	+
9		Comprehensibility of the visualization	+	−	+

3.2.1. LCSD

The LCSD is a flexible assessment tool for LCSA, as the accompanying software allows the user to personalize the visualization. Nevertheless, there are different types of criticism regarding the LCSD: Some critical points are not directly related to LCSD but rather to LCSA and the database, which is relevant for all of the named visualization tools (and future-developed ones). The choice of indicators, for example, can cause a certain subjectivity due to LCSA. Especially the choice of social indicators is a challenge with regard to their reliability and comprehension [15,28]. Another aspect arising from LCSA is the independent consideration of the different sustainability dimensions. The LCSD can offer solutions and identify the most sustainable option. Presenting unambiguous results is not always risk-free, as factors and indicators are often strongly interlinked. Adjusting one factor can lead to a 'backfire' effect, meaning that the adjustments can negatively affect another factor [29].

With the LCSD a form of presentation that fulfills the first two target criteria is enabled. The respective criteria for the evaluation of the three pillars of sustainability are listed in the lower area of the visualization. As the LCSD is an Excel macro and programmed for older Excel versions, the software is not available anymore (it would be possible to use the macro in an older Excel version). However, no explanation or reference to how the assessments were made is given in the visualization. Therefore, the third target criterion is only partially fulfilled (Table 1).

Within the visualization tool LCSD a color scale is used to illustrate the evaluation results. This so-called 'traffic light scale' was deliberately chosen by the authors because it is established in many areas and is therefore intuitively understandable. A legend for the color scale can also be shown. It is significant that the legend does not assign numerical values to the colors, but descriptions from 'excellent' to 'critical', which is why the fifth criterion is only partially met. A numerical result is displayed for the selected category in the upper area of the visualization. The dashboard is built to create a ranking between different products (worst has a value of zero, best a value of 1000). These are numbered in whole numerical values from first to last place. The flexibility of the visualization provides a large amount of information, which is not easy to grasp without access to the Excel macro due to continuing software actualization and stagnant macro. Therefore, the criterion of the appropriate quantity of information is only partially fulfilled (Table 1).

Due to the fact that the software for the LCSD is accessible free of charge (currently not available) [4], the assessment tool seems to be globally usable. Furthermore, the English language is used, which indicates the global applicability of the visualization. Therefore, the seventh criterion is assessed as fully met. The visualization appears to be adaptable and robust to changes and new findings in the field of LCSA due to the software and its flexible structure. The exact functionality of the visualization is not intuitively comprehensible without using the software and thus creating a barrier based on software reason is existent. The visualization itself does not offer a direct explanation of the calculated values and rankings without Excel, which is why the criterion of comprehensibility is rated as not obviously fulfilled (Table 1).

3.2.2. Crowns

The Sustainability Crowns do not represent an overall result of the LCSA, nor do they represent the results of the three sustainability dimensions. Thus, the Sustainability Crowns do not meet the first two evaluation criteria. According to Corona and San Miguel [20], the visualization should primarily support the user in weighing and combining the three pillars. The results are given concerning the arithmetic means of all alternatives for the respective criterion. However, a breakdown of how the respective result values are obtained is not shown. Therefore, the Sustainability Crowns only partially fulfill the criterion by providing a reference to the basis of assessment (Table 1).

A color scale based on the traffic light system is also used to illustrate the evaluation results of the criteria. In addition to the actual visualization, a legend is also presented that assigns each of the eleven colors used to an associated percentage range of results. The fourth target criterion is thus completely fulfilled. For the LCSA and the individual columns, neither numerical nor color results are presented. Furthermore, there are no numerical results assigned to the evaluation criteria in addition to the color coding. Therefore, the fifth criterion is not fulfilled. The Sustainability Crowns provide a quick overview of the results of the criteria used to evaluate the three pillars of sustainability. Corona and San Miguel [20] justify the omission of the results for the individual pillars by stating that their visualization approach is only intended to serve the user's weighting decision.

Due to the easy-to-understand structure of the figure and the use of the English language, the Sustainability Crowns seem to be globally applicable. Thus, the target criterion of the appropriate quantity of the listed data for the Sustainability Crowns is fulfilled. The representation form as a circle leaves room for flexible adjustments, both the criteria and the sustainability dimensions. Changes and innovations in the area of the LCSA should not require a new development of the Sustainability Crowns, which is why the criterion of adaptability is also fulfilled. The Sustainability Crowns have a clear structure, name the individual pillars, and use a common presentation of results in the form of percentage deviation from the average value, whereby the ninth criterion is also fulfilled (Table 1).

3.2.3. LCST

The visualization of the LCST helps the user to weigh the three sustainability dimensions. For example, if a user adjusts the given weighting set to his personal preferences, he/she can compare it with the weighting sets of products. However, no overall result of the LCSA can be obtained from the visualization itself. The pillars of sustainability are symbolized by the respective corners of the Triangle, but only the weightings of these and no evaluation results are presented. For this reason, the second criterion is not met (Table 1). An explanation of the evaluation criteria is not necessary, as the triangle is only used for weighting and not for evaluation. Furthermore, Müller and Hiete [21] criticize that the LCST cannot evaluate different scenarios in the visualization, and thus the LCST is not adaptable to external adjustable circumstances that are to be compared.

From a graphical point of view, the LCST represents a black-and-white illustration in which the weightings can be drawn in by the user in color. However, there is no anchored color scale corresponding to the criterion to illustrate the results. As explained before, only percentage weightings are given in the LCST. Since the fifth objective criterion (Table 1) aims at illustrating numerical evaluation results, the criterion is not fulfilled by the LCST. The LCST is only used to visualize the weighting of the sustainability dimensions. Therefore, the visualization fulfills the criterion of the quantity of information.

This visualization tool is an adaptation of the weighting triangle for the representation of chemical mixtures, which speaks for global and interdisciplinary applicability. In addition, the use of the English language suggests a worldwide comprehensibility of the visualization tool. Any three parameters can be selected. However, a change in the number of parameters would pose a problem, since this would require new development and naming of the visualization. Thus, under the condition of exactly three parameters, the LCST applies to arbitrary weighting problems, which is why the eighth criterion is partially fulfilled (Table 1). Furthermore, the user is provided with explanations for the abbreviations of the weighting factors.

3.3. Discussion

Considering all the information obtained, the LCSD is a very comprehensive visualization tool for LCSA. It fulfills most of the established comparison criteria for good visualization of LCSA (Table 1). The given flexibility of the visualization, which can be individually adapted by each user on the basis of the free Excel-macro, offers a great advantage. However, this flexibility also complicates the intuitive understanding when using the visualization without the help of a previous explanation of the ranking system. Due to the different output forms of the visualization for every application, the comprehensibility of the representation by third parties suffers. Another weakness of the visualization is the lack of a legend that assigns concrete numerical values to the colors instead of literal descriptions. This reduces the usefulness of the visualization, for example, for the precise comparison of the sustainability rating of products. A reference to the assessment basis of the individual criteria, in addition to the associated software, would also be useful for transparency reasons. With the help of the software, good comprehensibility may be ensured, but in a best-case scenario, the visualization should also be intuitively applicable and understandable independently of the software. Overall, although the LCSD provides much information and is the first known visualization approach specifically for LCSA results, the dashboard itself without the Excel macro support lacks a clearly structured design, which makes the application of the visualization very difficult.

The Crowns represent the latest published visualization approach for LCSA. It can be observed that Corona and San Miguel [20] have already recognized some weaknesses of the previous visualizations and have taken them into account in their approach. Similar to the LCSD, the Crowns also use a traffic light scale to visualize the assessment results. The associated legend provides the user with a percentage range of scores relative to the average score for that category. This is a good basis for purchase decisions by consumers who have to decide between several products on the market. However, the Sustainability Crowns do not map overall results for LCSA nor for the individual columns. Corona and San Miguel justify this in their publication by stating that the Sustainability Crowns should only be used as an aid for weighting in decision-making processes. Nevertheless, an overall assessment is an essential component for the use of visualization in practice. The value should be easily accessible and not discourage users with additional effort. The possibility of personal prioritization of different criteria by the user is not limited by the listing of additional results and should therefore be executed.

Compared to that, the LCST allows the user a simple classification of the weighting of the three sustainability dimensions. Additionally, the possibility of personal weighting is given and users can, for example, compare alternatives according to different weightings. Since the visualization of the LCST only shows the weighting sets and does not include any ratings, a comparison with the LCSD or the Crowns is rather difficult. According to the authors, the Crowns are also intended to serve only the weighting decision, but unlike the LCST, they map the evaluation criteria and their results. The LCST is rather unsuitable as an objectively usable interpretation approach in practice since the calculations for the sustainability assessment are only made after the visualization has been used to aid weighting and are thus dependent on these subjective weightings. Therefore, this visualization is mainly recommended as an additional decision-supporting tool.

In conclusion, it can be stated that the LCST and the Crowns represent easily comprehensible visualizations for the weighting of the pillars of sustainability, whereby the Crowns are convincing due to their clear structure. Only the LCSD transparently discloses the underlying LCSA results—with the help of the Excel macro. The flexible customizability of the dashboard is a key strength of the dashboard, but at the same time leads to a high degree of complexity, which makes it more flexible and by this partly more difficult to decide on and use in practice. Further development of an LCSA visualization tool that combines both the level of information and straightforward usability for users should provide a basis for decision-making for science and practice in the future.

4. Theoretical Future Development—Visualization Tool: LCSA-Wheel

Named weaknesses from existing visualization tools are subsequently revised and optimized in the following presented (initially theoretical) visualization approach for LCSA—named the LCSA-Wheel. The goal is to develop an instrument that can be used as a standardized application and interpretation approach in science and practice—used by experts and non-experts.

The target criteria as named in the previous chapter (Table 1) are adopted and serve the development. Thus, for the visualization, a form of presentation has to be found, which provides the user with the results of the LCSA, as well as the results of the three pillars at first glance. The evaluation criteria used and the corresponding results of these should be depicted. Besides the pure drawing, the transparent presentation of the origin of the results of the evaluation criteria is a crucial part of the visualization. This must either be directly readable or be retrievable by interested users without additional effort. The scope of the listed information must not leave any information gaps, but at the same time, should not scare off the user with a flood of information. A color scale with a corresponding legend should be used for visual clarification of the results. However, to be able to compare products in practice based on the LCSA-Wheel, for example, it is also necessary to display numerical results. To justify the effort and costs involved in creating a new interpretation approach of the LCSA, the global applicability of the visualization should be aimed. This can be achieved for both the visualization and the data basis by using a globally established language. The data basis is, therefore, to be covered in the future preferably by a freely accessible internet page, which at this place exceeds the scope of a visualization tool. Nevertheless, in general, it is a very important aspect to be discussed for the future of LCSA—partly already existing e.g., OpenLCA. Another target criterion for visualization is flexible adaptability. The visualization as such must therefore be flexibly expandable to different numbers of evaluation criteria or new dimensions of sustainability and apply to all sectors. A decisive factor for the implementation of visualization in practice is an easily understandable presentation. This must not be too extensive, but at the same time, it must contain all the necessary information. Through the preceding analysis and discussion, it has become apparent that the Sustainability Crowns fulfill most of the established target criteria for the visualization of the LCSA (Table 1). Therefore, the basic shape of the Sustainability Crowns visualization as a circle with surrounding criteria was deliberately adopted and adjusted. The visualization—named 'LCSA-Wheel'—was further elaborated after firsthand sketches with the free student version of the CAD program "ArchiCAD".

4.1. LCSA-Wheel

Figure 5 shows the 'LCSA-Wheel'. The naming is based on the one hand on the wheel-like appearance of the visualization and on the other hand on the symbolic character of the wheel, which literally keeps on turning, but has not been and does not have to be reinvented. This also applies to the developments in the field of LCSA and interpretation/visualization.

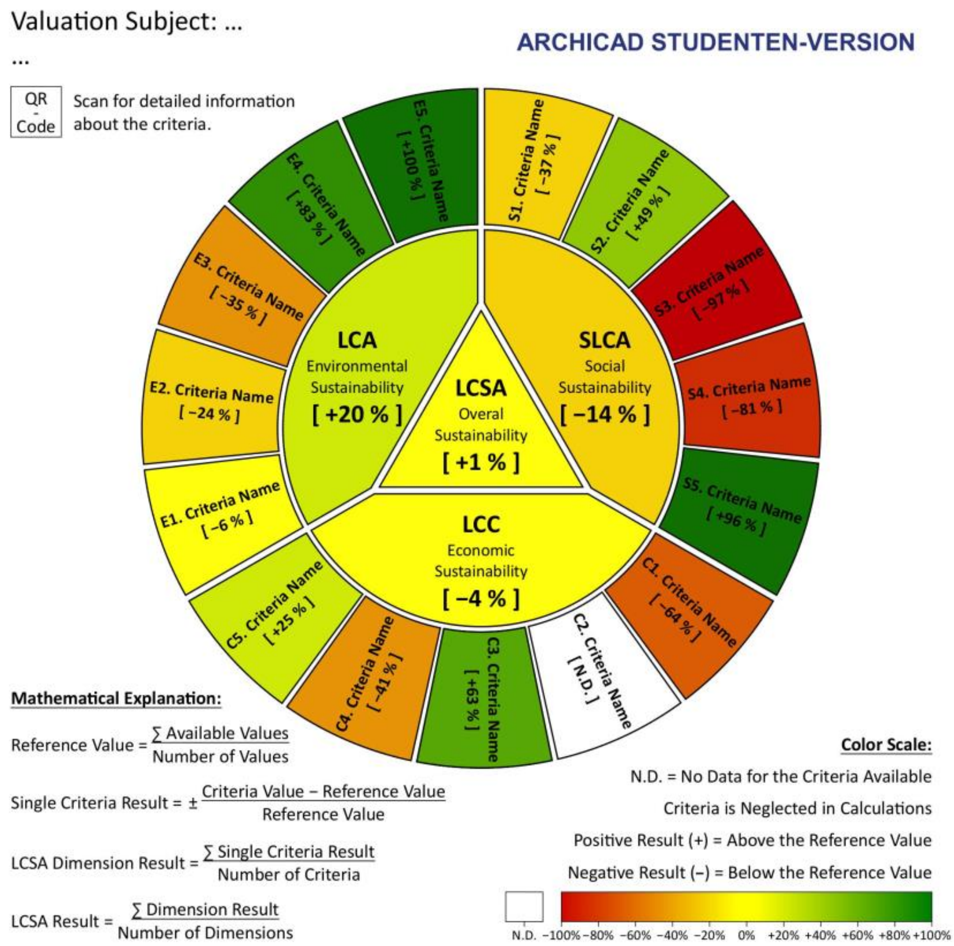

Figure 5. Future Development LCSA-Visualization: LCSA-Wheel.

The proposed visualization consists of the LCSA-Wheel, which presents the results of the sustainability assessment under consideration, as well as a frame that serves to provide further information and explanations to the LCSA-Wheel:

In the upper left corner, the assessed object, and any special features of it are indicated. Located below lies a QR code for further information, which leads the user to a stored website if desired (until now: theoretical development).

The mathematical calculations on which the results shown are based are listed in the lower-left corner of the image. The LCSA-Wheel always represents a questioned sustainability performance of a product or service in relation to a reference value/more reference values. This reference value can be another product or service the questioned one should be compared with, it can be a literature value, an official benchmark, or a value given by a database. Important is, that the reference value is clearly named and described and the respective source of information is provided. The mathematical calculations are explained in the following: First, the reference value is defined for each evaluation criterion by dividing the sum of all available reference values for a criterion by the number of these. For comparison purposes, literature values of scenario values can be used as reference values—if the functional unit, system boundaries, and full assessment are fully comparable. For LCA and LCC, the authors expect it to be easier to find reference values or even values. For S-LCA this might be a more complex and challenging task. Nevertheless, also the S-LCA values should be comparable, otherwise, the visualization in colors is not possible within the proposed LCSA-Wheel.

$$\text{Reference Value} = \frac{\sum \text{Available Values}}{\text{Number of Values}} \tag{3}$$

In the second step, the single criteria result of the object to be evaluated is calculated in the form of the deviation from the average criteria result. For this purpose, the defined reference value result is subtracted from the criteria value, and the resulting difference is divided by the reference value (only if a comparison is needed/wanted). For this second calculation, there needs to be a differentiation between LCA and LCC vs. S-LCA. The reason for this is, that a positive value as single criteria result would for LCA and LCC mean that the product or service questioned has a higher value than the reference value, which for both, emissions and costs, is seen as a negative aspect (see Equation (4). For S-LCA, the result is to be considered exactly the opposite. So, the signs for the respective columns have to be varied as follows: for LCA and LCC minus is needed, for S-LCA the plus stays see also the following case study for improved understanding).

$$\text{Single Criteria Result} = \pm \frac{\text{Criteria Value} - \text{Reference Value}}{\text{Reference Value}} \tag{4}$$

Next, an average result is calculated for each sustainability dimension using the arithmetic mean (LCSA Dimension Result). This is useful to gain an overview of how the assessed product performs within the sustainability dimensions considering different criteria. It provides users the opportunity to make decisions according to an overall sustainability performance within a particular dimension. For this purpose, all single criteria results of the respective dimension are added up and then divided by the number of criteria.

$$\text{LCSA Dimension Result} = \frac{\sum \text{Single Criteria Result}}{\text{Number of Criteria}} \tag{5}$$

Finally, the LCSA result is also obtained by adding up the dimension results and then dividing by the number of these results (LCSA Result).

$$\text{LCSA Result} = \frac{\sum \text{Dimension Result}}{\text{Number of Dimensions}} \tag{6}$$

The decimal numbers produced in the previously presented Equations (3)–(6) are displayed in the LCSA Wheel as integer percentages.

The lower right corner of the figure contains a legend of the used color scale. To enable intuitive comprehensibility, the use of the traffic light scale was chosen, just as for the LCSD and the Sustainability Crowns. The legend explains to the user the meaning of the colors used: white = no data available for the criterion under consideration, green = positive result that is better than the average result, and red = negative result that is worse than the average result. In addition, it is explained that a criterion for which no data is available is accordingly neglected in further calculations. Again, the color code is only needed/of relevance if the comparison is made (e.g., GWP/climate change values of different comparable assessments/scenarios).

The LCSA-Wheel represents the overall LCSA result, as well as the explanation 'LCSA Overall Sustainability' in the triangular box in the center of the circle. The LCSA result is shown as an integer percentage. For visual support, the color of the field corresponds to the result according to the assignment of the color scale. The results of the individual columns are shown adjacent to the three sides of the triangle. The results are presented in the same way as the LCSA result, using the color coding of the fields and percentage result values. The evaluation criteria including the respective results are again attached to the columns of sustainability at the edge of the circle. The designation of the criteria consists in each case of a letter, a consecutive number, and the name of the criterion. The letter E is assigned to the criteria of the LCA. Thus, the first clockwise criterion of the LCA dimension has the name E1, the second clockwise criterion E2, and so on. The LCC criteria are designated by the letter C and the S-LCA criteria are designated by the letter S and numbered sequentially in the same way as the LCA criteria. The results are presented similar to those of the LCSA and the three sustainability dimensions both by color and by percentage result.

Meeting the Target Criteria

The results of the LCSA and the individual columns are visible in the center of the LCSA panel in separate fields, thus fulfilling the first two target criteria (Table 1). To fulfill the third target criterion 'information or at least a reference to the basis of assessment' the evaluation criteria, including their obtained results, are mapped on the outer margin of the LCSA-Wheel. To ensure transparency of the origin of the evaluation criteria, a legend for the mathematical formulas used is integrated. Starting with the results for the individual criteria up to the overall result of the LCSA, this lists each calculation step in chronological order. To determine the criteria results, the respective value of the object under consideration is set to the average value of all available alternatives. In a globalized world, it is considered logical to include all available options in the evaluation of the criteria. Furthermore, to ensure transparency of information about the underlying data and evaluation criteria, compared scenarios or literature data should be shown and explained with the help of the QR code.

For the simultaneous fulfillment of the third criterion 'information or at least a reference to the basis of assessment' and the sixth criterion 'quantity of the listed information to suitable extend' it is decided to create two different output versions of the visualization: The first output or print version corresponds to Figure 1 presented earlier and is defined as the simple version. The second print version is presented in Supplementary Materials (Figure S1). This output version supplements the previously described standard version with a table containing additional information on the evaluation criteria. For each listed criterion, the total value of the considered object and the best-achieved value of all alternatives including the corresponding unit are shown. Additionally, the source is mentioned for traceability and transparency of the data, whereby, target criteria three and six are considered to be fulfilled.

The target criteria four 'use of a color scale including corresponding legend' and five 'information of numerical results (relative or absolute)' are completely fulfilled, since each result is always illustrated both in color and numerically. In addition to that, both formats are explained by a corresponding legend.

To fulfill the seventh criterion 'global applicability of the visualization and its associated data basis', the programming of a webpage for the underlying database could be useful, but may be difficult to implement due to known data and maintenance issues. The webpage should be globally usable and free of charge for all people. The maintenance of the database used must be ensured by qualified personnel, which can represent a challenge. What needs to be discussed at this point are the basic data, such as those offered by GaBi or Ecoinvent—which, however, are not free of charge and not freely accessible. Another requirement for global applicability is the language used. Since the English language is the most widespread and widely spoken, this is to be used on the webpage. For initial use of the LCSA-Wheel an Excel Sheet, resulting in the visualization of Figure 5 might be a part-time solution. In the long run, it does not represent a smart solution, which is why we propose the named webpage.

The fulfillment of the eighth target criterion, 'simple adaptability for new developments', is demonstrated by the illustration of two variants of the visualization described below. One of the variants is shown in Supplementary Materials Figure S2, which introduces a possible new dimension to the LCSA-Wheel. The introduction of one or even more new dimensions requires the adaptation of the fields but can be executed without redevelopment due to the flexible circular shape of the visualization. Supplementary Materials Figure S3 shows a second variant that represents the LCSA-Wheel with different numbers of evaluation criteria. As an example, six criteria for S-LCA, four criteria for LCC, and ten criteria for LCA were created. If an even larger number of criteria is required for an evaluation, these can also be added with little effort. The decisive factor here is that the criteria are named separately for each dimension using the letters introduced, thus preventing confusion. Thereby, if a new evaluation criterion is added for a dimension, a new criteria field is inserted clockwise at the last position of the dimension. This ensures the comparability of the visualization since the numbering of existing criteria is not changed by the insertion of new criteria.

The ninth target criterion, 'comprehensibility of the visualization', is difficult to evaluate objectively. Nevertheless, it was aimed to keep the structure of the visualization as simple as possible, with all necessary descriptions and explanations, to ensure the fulfillment of this target criterion. In addition, the LCSA and the individual columns were supplemented by short explanations of terms and a QR code so that users without prior knowledge of the field could also use the visualization.

4.2. Practical Example of Carbon Reinforced Concrete

To prove the applicability of the LCSA-Wheel and provide a short example, an implementation of LCSA results for carbon reinforced concrete based on previous studies [30,31] is conducted in the following. The system boundary is defined as cradle-to-gate, and the functional unit is defined as a double wall made of carbon reinforced concrete—based on and as a continuation of a previous LCA.

LCA: The values considered for the LCSA-Wheel case study are all taken from the former published LCA. The values are obtained from primary and secondary data and the LCA was performed with the help of the software solution GaBi ts. Table 2 shows the environmental performance for the defined functional unit of a double wall within the system boundaries of cradle-to-gate for one possible fiber and concrete combination. Within the actual study, only three environmental midpoint indicators are represented: Global Warming Potential (GWP), Abiotic Depletion Potential fossil (ADPf), and Acidification Potential (AP). The authors just chose three different midpoint indicators to give an example of how the LCSA-Wheel could finally look like and how the calculations are to be used in practice—especially focusing on the signs.

Table 2. LCA results for Carbon Reinforced Concrete assessing different fiber options [30].

	Concrete 1 = CEM I 42.5; 700 kg Only Portland Cement, Less Quartz Sand		
	GWP 100 Years [kg CO_2 eq.]	ADP Fossil [MJ]	AP [kg SO_2 eq.]
Fiber 1 = Given impregnation; conventional energy use	754	6775	1.05
Reference Value	729	6380	0.97

For example, in the LCA results for a double wall combining fiber F1 and concrete C1, the calculations for single criteria results are as follows:

$$Single\ Criteria\ Result\ GWP = -\frac{754 - 729}{729} = 0.0342 = -3.34\% \tag{7}$$

$$Single\ Criteria\ Result\ ADP = -\frac{6775 - 6380}{6380} = 0.0619 = -6.19\% \tag{8}$$

$$Single\ Criteria\ Result\ AP = -\frac{1.05 - 0.966}{0.966} = 0.0870 = -8.70\% \tag{9}$$

This results in the following LCSA dimension result for the LCA of Carbon Reinforced Concrete based on the three criteria GWP, ADP, and AP:

$$LCSA\ Dimension\ Result\ (LCA) = \frac{-3.34 - 6.19 - 8.70}{3} = -6.08\% \tag{10}$$

These results can be illustrated with the LCSA-Wheel (Figure 6) and thereby show precisely the results obtained from the Life Cycle Assessment. All relevant information that is necessary to understand and possibly compare the results, such as the criteria considered and the comparative products to which the results are related, in future should be found on the visualization itself and the data stored behind the QR-code (currently an Excel sheet which definitely needs to be improved in future for common use).

In our specific case, the color is presented in yellow, which means, that the questioned double wall (combined of F1 and C1) is more or less equally good or bad as the reference value, which is also visible in Table 2—for only two values one could still consider the table, comparing more than just two values, the LCSA-Wheel becomes even more important for a fast and easy comparison.

LCC: For LCC, actually there is no reference value for the questioned double wall available, which is why no color and number relative number can be presented. A total cost for the double wall could have been assumed, but just this absolute value will not allow us to use the LCSA-Wheel wisely. Especially for LCC, but also for S-LCA, it might be important to cooperate with the industry, as this would provide a full value chain and is often considered confidential costs. At this point it becomes clear for whom the LCSA-Wheel approach can be of greatest importance: industry or business, which wants to compare a variety of its own products with known manufacturing routes and costs.

S-LCA: Since currently quantified values for the S-LCA of carbon reinforced concrete are missing and there are also no quantitative reference values at this point, there are no numbers given in the practical example of the LCSA-Wheel (white color: no data), but the as mainly identified relevant indicators are presented in the visualization—named as workers health and safety, working hours adequacy and workers social security (see Figure 6).

LCSA: As in this case study we only were able to provide absolute values and reference values for LCA, the LCSA Results (overall sustainability) equals the LCSA Dimension Result.

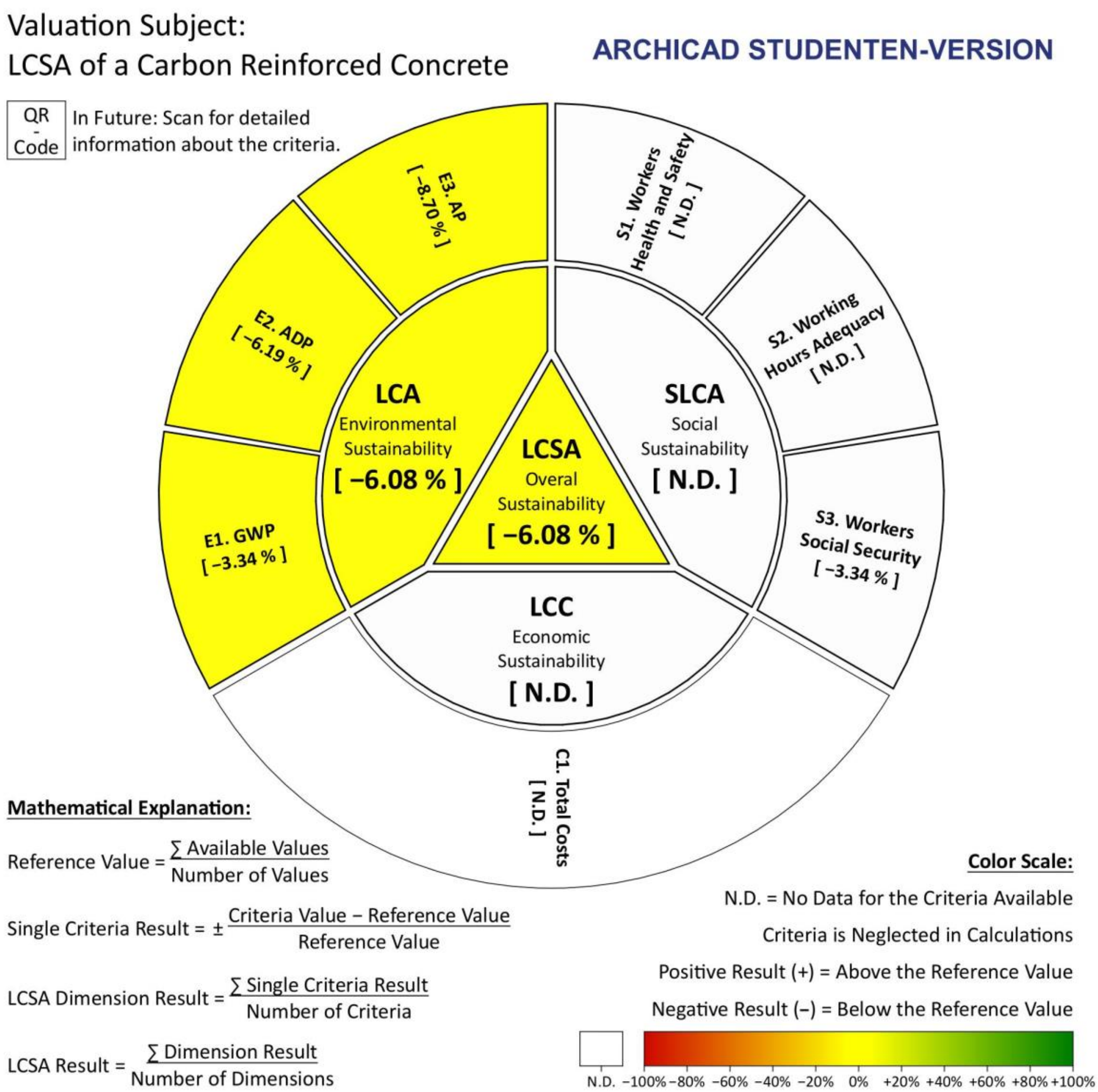

Figure 6. LCSA-Wheel for Carbon Reinforced Concrete.

4.3. Discussion & Limitation

The LCSA-Wheel was specifically designed for the visualization of LCSA results. All established target criteria to enable a good visualization of LCSA results are fulfilled, which shows that the LCSA-Wheel is a clear further development and improvement of the assessed three existing visualization tools. With regard to the LCSD, a clear and fixed structure is used, as well as additional explanations of terms. This creates a more user-friendly visualization that allows direct applicability for both non-specialist and expert users. Compared to the LCST, it can be stated that the LCSA-Wheel does not offer the possibility to introduce individual weightings. The evaluation criteria are equally weighted to calculate the sustainability dimensions. Similarly, the three sustainability dimensions are each equally weighted by one-third to determine the overall LCSA score, which is consistent with the approach of the LCSA [5,6]. This can be noted as a criticism of the visualization approach but has been deliberately implemented in this way with a view to the comparability of the visualization. For this approach, support is provided by a limit conjoint analysis conducted by Tarne et al. [32]. The analysis of the conducted survey of 54 decision-makers of a German automotive company showed that the three sustainability dimensions are weighted almost equally. On average, the economic dimension was weighted at 33.5%, the ecological dimension at 35.2%, and the social dimension at 31.2% [32]. As this corresponds to an approximately equal distribution, our approach of not including a weighting option in the visualization is supported by the study. Due to the improvements made over previously introduced visualization approaches, the LCSA-Wheel has the potential to become a standardized application and interpretation approach in science and practice. A limitation at this point is the lack of testing of the visualization tool by non-specialist and expert users and the differing calculations for LCA and LCC versus S-LCA (negative/positive single criteria result). This should be strived for in the next step for further optimization of the LCSA-Wheel—which additionally requires more practical implementation and thus programming in addition to the current theoretical approach. Furthermore, the data basis is an issue that still needs to be addressed: preferably open access data is used, which can mean, for example, coupling to OpenLCA. At the same time, the data basis in paid software solutions/databases such as GaBi or Ecoinvent is much larger and verified by third parties. Another—but more expensive—approach could therefore be for software providers to include visualization in their packages in the future. Special attention must be paid to the calculation so that the signs are not mistakenly reversed in the second calculation. At this point, however, the case study should have provided the reader with a full understanding. Particularly during the implementation of the case study, it became clear that data regarding LCC and S-LCA are relevant, otherwise, the visualization only makes limited sense. Cooperation with or explicit alignment of the LCSA wheel for the industry could be a solution at this point. This cooperation could also ensure an optimized application since data from software solutions have been transferred to Excel up to now and there is still no improved application. This must be changed in the future and improved in terms of user-friendliness.

5. Conclusions

The aim of this publication was the elaboration and presentation of already existing LCSA interpretation and visualization tools, as well as the further theoretical development of a visualization tool for Life Cycle Sustainability Assessment results, which can establish itself in science and practice as a standardized application and interpretation approach. First, all existing approaches were described and three focused approaches (Life Cycle Sustainability Dashboard, Life Cycle Sustainability Triangle, and Sustainability Crowns) were methodically compared. The comparison showed the following key results:

- The Life Cycle Sustainability Triangle is rather unsuitable as an objectively usable interpretation approach in practice since the calculations for the sustainability assessment are made only after the visualization has been used to aid weighting and are thus dependent on subjective weightings. It is therefore recommended as an additional tool for decision support.
- The Life Cycle Sustainability Dashboard is a very comprehensive visualization tool for LCSA results. It provides the user with some information, but it lacks a fixed and structured structure, which makes the application of the visualization very difficult.
- The Sustainability Crowns are only intended to help the user weigh the sustainability dimensions and therefore do not map overall results. Nevertheless, the Sustainability Crowns fulfill most of the established target criteria and have an intuitively understandable structure.

The Sustainability Crowns served as a model for the development of the more advanced (so far theoretical) visualization approach: the LCSA-Wheel. This approach is suitable for illustration and discussion of LCSA results in both science and practice. It can be described with the following key characteristics:

- A circular illustration was supplemented by a frame that provides the user with further information, such as mathematical explanations of the calculations. Furthermore, the overall results were vividly added to the center of the LCSA-Wheel, as these form the core of the visualization.
- It can be chosen from multiple print versions: The first includes the LCSA-Wheel with a QR code, which can be used to access the stored data basis in the form of a

website. The second print version supplements the LCSA-Wheel with a table that lists information about the evaluation criteria used.

- Flexible application is possible by adjusting the number of evaluation criteria and the sustainability dimensions.

An essential component of the visualization tool, besides pure visualization, is the associated data basis in the form of a website. In the next step, the website has to be programmed and created according to the specifications and contents. Furthermore, the contained data (preferably open access, for example, linked to OpenLCA) must be permanently maintained and updated. This incurs costs for the employment of expert personnel. Another decisive factor for the implementation of sustainability assessment in science and practice is the final standardization of the LCC and the S-LCA. The lack of standardization to date makes it difficult to collect data for the two sustainability dimensions, and the comparability of collected data cannot be guaranteed without standardization. In order to finally establish the LCSA framework in science and practice, these two pillars of sustainability need to be standardized in a timely manner within a similar framework to the LCA. Looking back on the work presented, it can be concluded that the LCSA holds great potential for the future, regardless of the industry, and that the LCSA Wheel developed can complement the LCSA framework as a suitable visualization tool when making use of a webpage/QR code and working in general on the named data challenge.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su151310658/s1. Figure S1. Future Development LCSA-Visualization: LCSA-Wheel—detailed version; Figure S2. Future Development LCSA-Visualization: LCSA-Wheel—additional dimension; Figure S3. Future Development LCSA-Visualization: LCSA-Wheel—additional criteria.

Author Contributions: Conceptualization, J.G.B.; methodology, L.S.S. and J.G.B.; software, L.S.S.; validation, J.G.B., A.W., M.T. and L.S.S.; formal analysis, L.S.S., J.G.B. and A.W.; investigation, L.S.S., J.G.B. and A.W.; resources, L.S.S. and J.G.B.; data curation, L.S.S., J.G.B. and A.W.; writing—original draft preparation, L.S.S. and J.G.B.; writing—review & editing, L.S.S., J.G.B., A.W. and M.T.; visualization, L.S.S.; supervision, J.G.B. and M.T.; project administration, J.G.B.; funding acquisition, J.G.B. and M.T. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the German Research Foundation (DFG), as part of the Sonderforschungsbereich/Transregio 280 (SFB/TRR 280) 'Konstruktionsstrategien für materialminimierte Carbonbetonstrukturen'/'Design Strategies for Material-Minimized CRC Structures' (Subproject E01, project number 417002380). The financial support by the German Research Foundation (DFG) is gratefully acknowledged.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available in this study and its Supplementary Materials.

Conflicts of Interest: The authors have no conflict of interest to declare.

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Total number of authors:
13

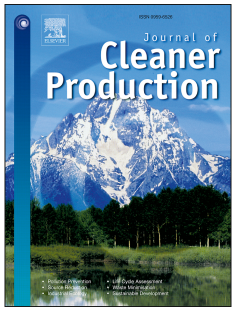
Published in:
Journal of Cleaner Production

Link to article, DOI:
10.1016/j.jclepro.2019.118271

Publication date:
2019

Document Version
Peer reviewed version

Journal Pre-proof



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PII: S0959-6526(19)33141-5

DOI: https://doi.org/10.1016/j.jclepro.2019.118271

Reference: JCLP 118271

To appear in: *Journal of Cleaner Production*

Received Date: 28 October 2018

Revised Date: 30 August 2019

Accepted Date: 2 September 2019

Please cite this article as: Blomsma F, Pieroni M, Kravchenko M, Pigosso D, Hildenbrand J, Kristinsdottir AnnaRù, Kristoffersen E, Shabazi S, Nielsen KD, Jönbrink A-K, Li J, Wiik C, McAloone TC, Developing a circular strategies framework for manufacturing companies to support circular economy-oriented innovation, *Journal of Cleaner Production* (2019), doi: https://doi.org/10.1016/j.jclepro.2019.118271.

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Abstract

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Keywords Circular strategies framework, closed loop, resource productivity, manufacturing companies, innovation.

Acknowledgements

This article is one of the outcomes of the research project CIRCit (Circular Economy Integration in the Nordic Industry for Enhanced Sustainability and Competitiveness), which is part of the Nordic Green Growth Research and Innovation Programme (grant numbers: 83144) and funded by NordForsk, Nordic Energy Research, and Nordic Innovation. We would also like to thank the companies participating in the CIRCit project and the anonymous reviewers whose thoughtful feedback aided the development of this work.

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1. Introduction

The linear economy is frequently characterised by the presence of structural waste: instances where components, products or materials reach their end-of-use/life prematurely, or where their capacity for value creation is underutilised. To address this, the circular economy (CE) concept proposes a range of efficiency and productivity enhancing activities collectively known as circular strategies, such as reduce, reuse, repair, recycle, restore, cascading, etc (EMF, 2013). In this sense, CE is an umbrella concept: it groups a range of sub-concepts and imbues them with a new meaning by highlighting a shared feature of the sub-concepts (Blomsma and Brennan 2017). This new meaning revolves around the notion that through the application of circular strategies both more value can be created (EMF, 2013) as well as value loss and destruction reduced (Murray et al., 2015).

Although CE has widely been recognised as an idea with potential merit, it has yet to be widely implemented and embedded within business and industry (Haas et al., 2015; Circle Economy 2019). This is in line with the progression of umbrella concepts: when the transformative potential of an idea has been recognised, the attention then turns to operationalising it through frameworks, tools, methods and approaches. This, in turn, allows for further examination of the concept.

For CE this means that there is currently a focus on developing CE transition methodology. This is taking place in a number of aspects relevant for Circular Oriented Innovation (COI) (Brown et al. 2019), such as in business models (Bocken and Antikanen 2018; Pieroni et al. 2019; Rosa et al. 2019), metrics and assessment (Kravchenko et al. 2019; Moraga et al. 2019; Saidani et al. 2019), product design (Moreno et al. 2016; Den Hollander et al. 2017) and the creation of organisational capabilities such as experimentation, value chain innovation and other human factors (Weissbrod and Bocken 2017; Chiappetta Jabbour et al. 2019; Nilsson-Lindén et al. 2019).

Previous academic work focuses on answering 'what' or 'how' to promote COI (Guzzo et al. 2019; Mendoza et al. 2017). However, supporting the early stages of COI through the establishment of a CE vision, i.e. answering

why to perform COI, has so far achieved relatively little scholarly attention. Finding the 'why' for a CE transition, requires understanding the type of structural waste in the system, which can be accomplished with a systemic analysis/diagnosis across life cycle stages and various business processes and knowledge areas. This requires various actors within and across business to define and explore problem and solution spaces together (Brown et al., 2019). Specifically, in COI a high-level conceptual understanding of CE needs to be translated into a vision that is useful and meaningful on the level of decision making (Hoffman, 2003; Boons and Howard-Grenville, 2009; Lindkvist and Baumann, 2014). The importance of a shared vision in innovation projects has long since been acknowledged (Pearce and Ensley, 2004; Bititci et al., 2004), and it has been posited to be relevant for both inter and intra organisational COI efforts (Brown et al., 2019).

Currently, there exists a range of frameworks that could potentially be drawn from to support CE visioning. These take the form of circular strategies frameworks, such as the ReSOLVE framework (EMF, 2015), the Performance Economy (Stahel ,2006), Cradle-to-Cradle™ (Braungart and McDonough, 2002), and the Waste Hierarchy (EC, 2008), but also the Ricoh Comet Circle™ (Ricoh, 2018), the Seven Fronts of Mount Sustainability (Interface, 2018). Importantly, these frameworks can be seen as the visual representations of a vision for how to operate in a CE, since they select, name and organise circular strategies seen as relevant, such that their relationship becomes apparent.

However, Mendoza et al. (2017), Reike et al. (2017) and Blomsma (2018) observed that such circular strategies frameworks can identify or emphasise different (groups of) circular strategies, which can be linked to addressing different types of structural waste. As such, there is a risk that they do not include circular strategies with transformative potential for a particular context. Moreover, Blomsma (2018) points out that little work has been done with regard to ensuring that frameworks are seen as relevant and useful by their intended audiences. For these reasons, there is scope to further develop these frameworks to support visioning in COI. Mendoza et al. (2017), Niero and Hauschild (2017) and Blomsma (2018) therefore call for the development of such frameworks within academia.

This paper answers this call and addresses the question of how to develop circular strategies frameworks such that they are relevant for their intended audiences, in a manner that points to the transformative potential of CE and that assists with unpacking the complexity associated with COI. With this, this paper contributes to the body of work that develops CE transition methodology, focussing on the early stages of COI and engaging the affected audiences in a transdisciplinary approach (Sakao and Brambila, 2018).

As an illustrative case, we develop a circular strategies framework for manufacturing companies1. Manufacturing companies were chosen as the focus as they are important users of materials and energy, produce significant amounts of byproducts traditionally regarded as waste, and form an important employment sector2 and contributor to GDP (Rashid et al., 2013). In addition, manufacturing companies play an important role in the creation of value to their customers and therefore have great potential to decouple this value provision from linear resource consumption.

After clarifying the research gap in the background section and exploring the shortfalls of current circular strategies frameworks to support COI within manufacturing, we continue with setting out the methodology applied in this paper. In the following sections we present the development of the criteria used for designing the new framework and explain the relevant details and outcomes of each subsequent development phase. Furthermore, in section 6, we provide an example of application of the framework in COI. We close with a discussion of the contributions of this paper and directions for further work.

[1] We use the expression *manufacturing companies* to refer to secondary manufacturing, as opposed to primary production. Moreover, these companies are not contract manufacturers, but have a degree of control over their supply chain.

[2] Sector, as used here, refers to an area of economic activity such as food, medicine, construction, etc. See: https://unstats.un.org/unsd/classifications/.

2. Background and research clarification

Describing the complete landscape of circular strategies frameworks is beyond the scope of this paper. However, here we provide an overview of the current landscape of circular strategies framework, through offering a typology of five classes of frameworks. The first four classes describe a continuum where the scope becomes increasingly smaller: (1) the macro level of industrial systems or economies; (2) the meso level of sectors, materials and business types; (3) the micro level of companies; and (4) the nano level covering product (groups) (Saidani et al., 2017). The fifth level adds the layer of (5) networked and regional approaches, through which the other four levels are connected. See Figure 1.

Overview of the landscape of circular strategies frameworks

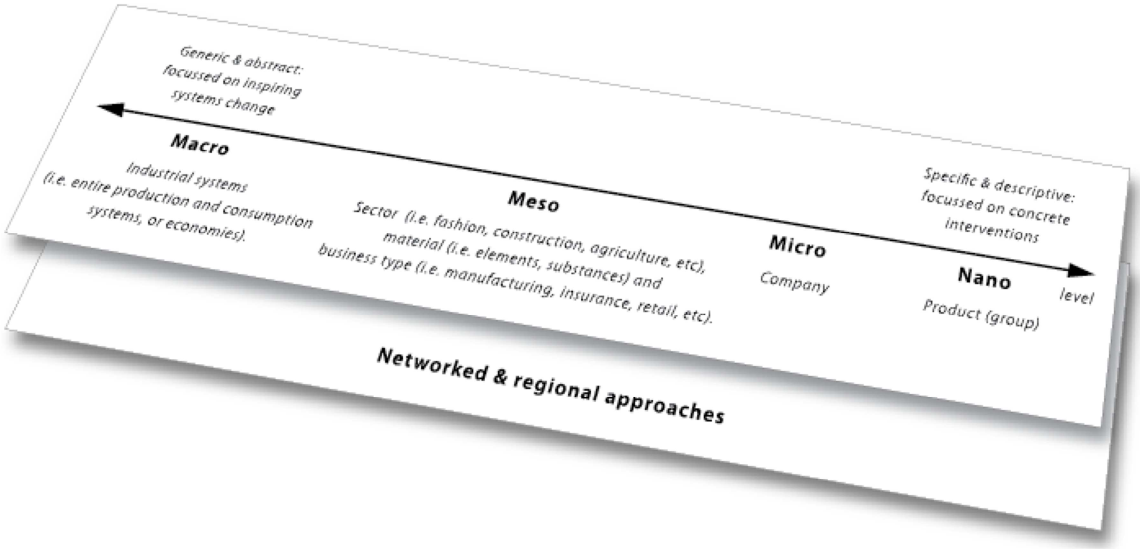


Figure 1. Schematic illustrating the coverage of frameworks on the macro-meso-micro-nano scale, and their relationship with frameworks covering networked and regional approaches.

Considering the landscape of current circular strategies frameworks, a number of observations can be made that explain why current circular strategies frameworks fall short in their capacity to support visioning for manufacturing. First, a circular strategies framework needs to create a comprehensive understanding of circular strategies, as relevant for the purpose (Brown et al., 2019) and context (Blomsma, 2018). Think, for instance, of the difference in the main functions of insurance and finance firms, retail and wholesale businesses, service providers, and manufacturing companies. Different circular strategies will be relevant in these contexts (Rashid et al. 2013; Johannsdottir 2014; Upadhyay et al., 2019).

Currently a multitude of frameworks exist on all levels of the landscape. See for frameworks on the macro level, for example: Allwood et al. (2011), Reike et al. (2018), Bocken et al. (2016), or Braungart and McDonough (2002). Likewise, for meso level frameworks for materials, see for water (WssTP, 2015) and biomass (ECN, 2018); or fashion and textile frameworks by EMF (2017), Inditex (2016) and Mistra Future Fashion (2018). On the micro level, consider: Gispen's (2018) framework for circular furniture, *The 10 R's of Circularity* by (Mitsubishi Electra, 2018), the Ricoh Comet Circle™ (Ricoh, 2018) (first used in 1994), or the framework used by Konecranes (2018). Likewise, on the nano level: Circular Jeans by Levi Strauss & Co. (2015), and Re-Entry for carpet tiles (Interface, 2016). Lastly, on the networked level, consider: Ehrenfeld and Gertler, 1997; Aguinaga et al., 2018; Pauli, 2010.

A notable exception of circular strategies frameworks exists on the meso level that apply to specific business types, in particular to manufacturing. One exception is the ResCom framework by Rashid et al. (2013), which targets manufacturing companies. However, this framework is also not well suited to supporting innovation processes, as it includes few circular strategies and contains a limited consideration of business processes.

In addition to creating a comprehensive understanding of circular strategies, a circular strategies framework that supports visioning needs to both map strategies currently applied as well as find opportunities for improved circularity for a range of business processes from a systemic point of view. In this aspect, current frameworks are also lacking as they are often derived or compiled to serve as a summary or overview of a piece of (mostly theoretical) work, as opposed to being purposefully developed for use in COI in and with businesses (Niero and Hauschild, 2017; Kalmykova et al., 2018; Blomsma, 2018; Sakao and Brambila, 2018). However, to establish a vision it is important to both understand the current situation - e.g. what is already being done towards CE, or what capabilities provide a basis for this, as well as to identify what opportunities are present and desirable. Current circular strategies frameworks are not designed to capture an overview of both the current situation and ideas for future innovation.

Another shortcoming of current circular strategy frameworks is that they exhibit ambiguity with regards to the meaning of and relationships between the included circular strategies, allowing the same term to adopt multiple meanings - sometimes with radically different outcomes from a resource perspective (e.g. whether recycling keeps material quality on a consistently high level, or whether it represents downcycling) - or to be rendered inapplicable to some contexts (Reike et al., 2018; Blomsma, 2018).

This paper addresses these shortcomings, by a) providing an example of a process of how a circular strategies framework can be developed for a specific business type with the ability to support COI processes, b) proposing a circular strategies framework for the manufacturing context, resulting in the Circular Strategies Scanner, with c) an accompanying set of definitions of circular strategies (including commonly used synonyms). In addition to this, we provide d) an example of how such a framework can be used to structure and guide the early phases of COI, in order to show the relevance of visioning approaches within CE transition methodology.

3. Methodology

Design Research Methodology (DRM) was applied for the development of the new circular strategies framework for manufacturing, as this method is particularly suited to the deliberate iteration of methods and tools (Blessing and Chakrabarti, 2009). Next, a high-level overview of the aim and activities in each phase is provided. See Figure 2 for an overview: more details are provided in the sections dedicated to each respective phase. The development of the proposed framework took place from November 2017 to July 2019.

Research clarification - This phase, already discussed in the previous section, served to refine the research gap and identify the need for a framework specifically for manufacturing companies.

Descriptive study I - This phase served three goals. First, a list of circular strategies to be included in the framework was compiled. Second, criteria that could be used to guide the development process of the new framework were articulated, which, third, were used to choose an existing framework as the basis for the development of the new framework. A series of workshops and meetings were held for this purpose. Iterations of the strategies list, their definitions and the framework requirements were performed throughout the project, but are presented as a single phase for clarity and brevity.

Prescriptive study I - A series of workshops and follow-up meetings were held to conceptualize and develop a first version of the circular strategies framework, as well as the corresponding clarifications and elaborations on strategies, and the relationship between them.

Descriptive Study II - In this phase the applicability and usefulness of the framework in the context of the manufacturing sector was evaluated and improvement opportunities sought. Workshops were performed with three manufacturing companies from the heavy machinery, electronics and furniture sector.

Prescriptive study II - A series of meetings was held to discuss the implementation of the improvement opportunities, based on insights from *Descriptive Study II* and the iterations of the *Research Clarification* and *Descriptive Study I* phases. A second version of the framework and a final list of strategies and their definitions were developed during this phase.

Moreover, the approach applied was deliberately transdisciplinary. That is, it aimed for establishing "a common system of axioms for a set of disciplines," which was achieved in two ways (Sakao and Brambila-Macias, 2018:1400), see also Figure 2:

(1) *Adopting a systemic view* - In the context of (more) circular manufacturing this means the alignment of the different business processes, which together contribute to the creation of circular systems. The perspectives of these processes therefore need to be included.
(2) *Inclusion of non-academic stakeholders* - Creating (more) circular manufacturing systems entails affecting changes in manufacturing companies. As such, it is important to acknowledge the perspective of manufacturing companies in the development of the new framework.

The first type of transdisciplinarity was implemented through the creation of the CIRCit research consortium[3] to represent the knowledge related to business model strategy, product design, and a range of operational processes such as sourcing, manufacturing, logistics, through-life support, digital technologies and end-of-life operations, but also sustainability aspects and value chain management.

The second type of transdisciplinarity was implemented through application of the framework on retrospective company cases, as well as applying the framework in ongoing research that is actively supporting companies in implementing circular practices. Furthermore, the consortium contained representatives of the interests of manufacturing companies, such as industry associations. Through this, the perspective of 'real-world' considerations was added. Next, the outcomes of each phase is presented.

[3] See for more information about the consortium: www.circitnord.com.

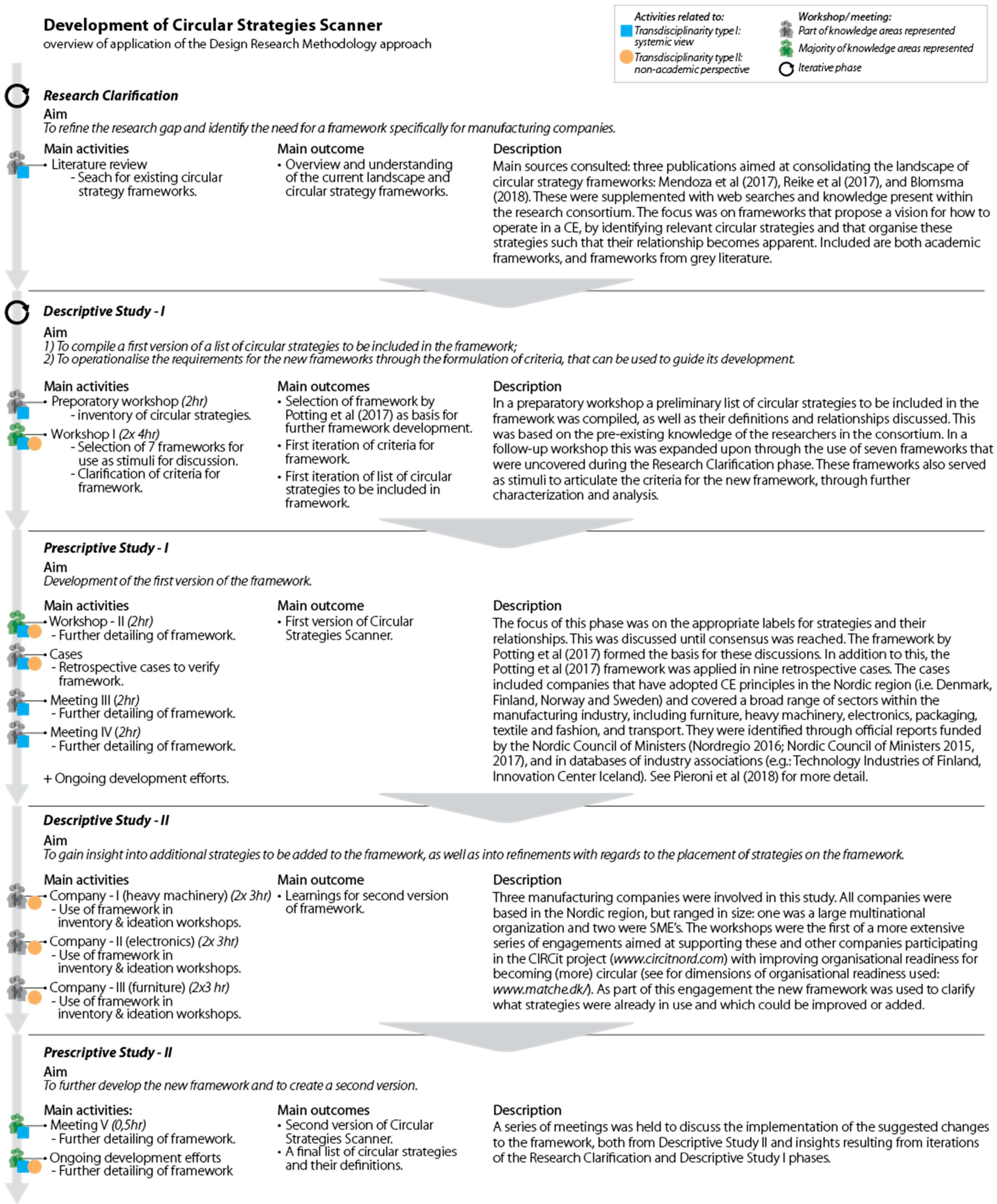


Figure 2. Schematic illustration of the approach followed for the development of the Circular Strategies Scanner.

4. Descriptive Study I - criteria for a circular strategies framework for manufacturing companies

This phase served to establish a foundation for the development of the new framework. This was done in the following manner, see also Figure 2.

4.1. Rationale behind Descriptive Study I

Due to the lack of suitable meso level frameworks with a business type orientation, macro frameworks were used as a starting point with the aim to adapt their generic applicability and generative capacity for manufacturing companies. From the macro frameworks 1) relevant circular strategies were extracted, and 2) criteria that could be used to guide the development process of the new framework were articulated, which 3) were used to choose the best fitting existing framework as the basis for the development of the new framework. In particular, seven macro level frameworks uncovered during the Research Clarification phase were used: Thierry et al. (1995), Parkinson and Thompson (2003), Allwood et al. (2011), Bocken et al. (2016), Nussholz (2017), Potting et al. (2017), and Blomsma (2018). These were included based on 1) their range of relevant strategies for the manufacturing context, 2) their inclusion of definitions and/or examples of these strategies and 3) representing a broad range of approaches to classify or organise the strategies in relation to each other. This served to have contrasting definitions and approaches that could be discussed and analysed.

4.2. Outcomes Descriptive Study I

The final version of the list of included strategies, their definitions and examples, which continued to be iterated throughout the development of the framework, can be found in Table 2 (see section 7. *Prescriptive study II*). Here, the focus is on the five criteria for the new framework that were developed to detail the main functions of a circular strategies framework (create understanding of CE, map current CE initiatives, generate ideas for increased circularity). The criteria were iterated until they represented five clear requirements for the development of the new framework. This section concludes with the selection of the best fitting existing framework.

Criterion #01: A tool for inspiring, motivating and aligning people

In innovation processes it is important to invoke relevant frames, acknowledge cognitive principles (which involve cognitive limits, but also principles of attention, inspiration and motivation) and, in collaborative settings, to consider the alignment of understanding, mindsets and interests between different stakeholders. Language, both visual and written, plays an important role in this: it helps directing attention, summarising and synthesising information from internal and external knowledge sources and it supports orientation towards relevant aspects of the context (Biloslavo et al., 2018; Breuer et al., 2018) and in the creation of a shared vision, also in the context of CE (Blomsma, 2018). Therefore, in line with the frameworks discussed above, the proposed framework should 01) represent a complex phenomenon in an easily accessible manner in order to inspire, motivate and align people.

Criterion #02: A tool for describing current situations and identifying opportunities, both incremental & transformative

A framework suitable for use by a wide variety of manufacturing businesses, cannot be broad in the sense of the frameworks on the macro level, as it will lose relevance. At the same time, it can also not be specific in the sense of the company and product frameworks, as this would mean it is limited in its reach and impact. However, the new framework should be suitable for describing both current initiatives and have the capacity to systematically explore relevant strategies and identify new opportunities. As such, the new framework should balance the strengths of the macro and meso level frameworks - which are generative and allow for the exploration of alternatives, with that of the micro and nano level frameworks - which offer greater specificity in relation to the context in which strategies are applied. Thus, the new framework should: 02a) balance the generation of new ideas, with that of describing existing situations. This indicates that it is preferable to include a diverse set of circular strategies, as opposed to high-level aggregated groups of strategies.

Furthermore, opportunity finding needs to point to the potential for improving existing strategies, as well as to radically different ways of achieving goals and creating, delivering and capturing value. This can involve the design, production and/ or transport of physical products, but it can also require a change in the business logic and operations that changes how products are commercialized and consumed. Think of the implementation of access-over-ownership models, or radical dematerialisation through a change in paradigm. As such, the framework should 02b) provide an overview of the spectrum of available strategies ranging from incremental to transformative. This indicates that the set of included strategies should cover strategic as well as operational business processes.

Criterion #03: A tool for facilitating alignment of changes in business processes and capabilities
Circular strategies frameworks aimed at specific business types need to provide insight into which business processes relevant for that business type need to be aligned. This means, following Allwood et al. (2011), Potting et al. (2017) and Reike et al. (2018), that the new framework should indicate which circular strategies may apply to which flows. In the manufacturing context, this implies 03) indicating which strategies affect which business processes and related capabilities.

Criterion #04: A tool for bringing together efficiency and effectiveness strategies, and strategy configurations
Following e.g. Pauli (2010), Stahel (2006), Potting et al. (2017), Reike et al. (2018) and EMF (2015), we adopt the view that both resource-efficiency and resource-effectiveness are important in the manufacturing context. The new framework therefore should: 04a) explicitly include the reduction and avoidance of resource use and impacts, as well as resource productivity strategies aimed at continued use and value delivery.

Moreover, many manufacturing companies operate in complex scenarios, that can be thought of as circular configurations: situations where two or more circular strategies are present (Blomsma and Brennan 2017, Blomsma 2018). Think of product/ service systems where direct reuse, but also repair, refurbishment and remanufacturing are taking place, in addition to the recycling of materials. As such, the proposed framework should: 04b) allow for generating insight into circular configurations.

Criterion #05: A tool for alignment with drivers: value creation & capture orientation
Businesses need to create and capture value to continue their activities. It is widely acknowledged that circular strategies have the capacity to contribute to this. However, not many current frameworks support the identification of the type of value that can be captured through which strategies. The new framework therefore needs to be aligned with the perspective of systemic value creation and capture. Support in identifying this can enable assessing and measuring outcomes and tracking potential deviations from the planned future state, which is fundamental to transition management (Breuer et al., 2018). As such, the proposed framework: 05) has to point to the value drivers that circular strategies can contribute to. That is: the framework has to help users identify relevant contributions to value creation and capture, such as improved efficiencies, supporting optimal use during the use phase, and value recovery opportunities, resulting in either financial or non-financial gains within or outside the company (Circle Economy et al., 2016). As these may be relevant for business shareholders, but also suppliers and customers, the environment and society they need to be formulated such that relevance for these stakeholders can be easily appreciated.

Next, the seven frameworks were compared and rated on these criteria, see Table 1. Although none have a perfect score, the framework by Potting et al. (2017) scores the highest: it represents a complex phenomenon in an easily accessible manner (criterion 01), contains a comprehensive set of circular strategies (criterion 02b), includes efficiency as well as effectiveness strategies (criterion 04a) and points to value drivers that circular strategies can contribute to (criterion 05). This framework was therefore chosen as a basis for further development of the new framework, with its relevance for different business processes and capabilities (criterion 03) identified as in need of further improvement.

Criteria The new framework should:	Bocken et al (2016)	Allwood et al (2011)	Parkinson & Thompson (2003)	Thierry et al (1995)	Potting et al (2017)	Nussholz (2017)	Blomsma (2018)
01) A tool for inspiring, motivating and aligning people.	+	++	0	++	++	+	+
02a) Balance the generation of new ideas, with that of describing existing situation.	0	+	0	+	++	+	0
02b) Provide an overview of the spectrum of available strategies ranging from incremental to transformative.	+	+	0	+	++	++	0
03) Indicate which strategies affect which business processes.	0	+	0	+	+	0	0
04a) Explicitly include the reduction and avoidance of resource use and impacts, as well as resource productivity strategies aimed at continued use and value delivery.	+	+	0	0	++	++	0
04b) Allow for generating insight into circular configurations.	+	++	0	++	++	+	+
05) Has to point to the value drivers that circular strategies can contribute to.	++	0	0	+	++	+	++
+++ = framework satisfies criterion very strongly, ++ = framework satisfies criterion strongly, + = framework satisfies criterion moderately, 0 = framework doesn't meet criterion or only marginally.							

Table 1 - Comparison of the seven frameworks that were used in Descriptive Study I using the development criteria.

5. Prescriptive Study I

During this phase the first version of the new framework was developed, through adding detail to Potting et al. (2017) as relevant for the manufacturing business type, guided by the criteria established in the above and the exploratory case studies (see Pieroni et al., 2018). The focus was on the appropriate labels for strategies, and how to convey the relationship between the included strategies.

5.1. Outcomes Prescriptive Study I

The outcomes of this phase is discussed in terms of the adaptations of the Potting et al. (2017) framework that were made. Only the major adaptations are elaborated upon: see for the first version of the framework Figure 3 and the complete set of changes Appendix A. See for definitions and examples of individual strategies Table 2 (section *7. Prescriptive study II*).

Major adaptations #01 and #02: Organisation of circular strategies according to business processes, and greater specificity for 'Reduce'

The preliminary list of circular strategies from the previous phase was organised according to the business processes as typically found in the manufacturing context, to meet criterion #03. For this, the process of transformation of raw materials into finished or intermediate goods was divided as follows. First, two areas that are related to the corporate strategy were identified: the first is changing the paradigm of practices and was named 'Replace,' and the second is a reconsideration of how value is delivered, entitled 'Rethink.' The former strategy enables radical dematerialisation through different ways of performing functions (e.g. functional replacement or new practices), which can be enabled by new technologies. This strategy was renamed from Potting and colleagues' 'Refuse' (see Medium adaptation 1 in Appendix A). The latter strategy involves new business models that are more resource efficient, such as access-over-ownership offerings, enabled by commercial models based on leasing, renting or pay-as-you-go. As such, 'Replace' concerns the

delivery of functionality through radically different means, whilst ‘Rethink’ delivers similar functionality through different customer relationships and which may involve a redefinition of the functional unit.

The remainder of the framework concerns operational processes. Potting et al’s (2017) ‘Reduce’ was further divided to make its application to the following operational processes explicit: ‘Raw materials and sourcing,’ ‘Manufacturing and logistics’ and ‘Product use/ operation.’ This indicates that in these phases, the focus is on efficient use of resources and the reduction of harmful impacts.

The next two operational process areas respectively contain various end-of-use and end-of-life strategies. The first contains the strategies ‘Upgrade’ (see Minor adaptation 2), ‘Repair & Maintenance’ (see Minor adaptation 4), ‘Reuse,’ ‘Refurbish,’ ‘Remanufacture,’ and ‘Repurpose’; and the second which contains the strategies ‘Recycle’ and ‘Recover’ (see Minor adaptation 1).

Major adaptation #03: Addition of the relationship between business processes
To capture the different relationships between the strategies (criterion 04b), a visual structure consisting of three levels has been created: the first occupied by ‘Replace,’ the second by ‘Rethink’ and the third by the remaining strategies. This is indicated by the relative placement of the boxes containing the strategies and the addition of arrows. This signals that, within the manufacturing context, some relationships between circular strategies are of a hierarchical nature, and some exist in the form of trade-offs and synergies. An example of a hierarchical relationship: ‘Replace’ may preclude the use of certain other circular strategies, when, for instance, a physical product is replaced by a virtual service. On the other hand, the application of ‘Rethink’ can require the support of repair and maintenance strategies to be viable, such as in certain product/service system offerings. As such, the application of either ‘Replace’ or ‘Rethink’ requires that the relevance of all strategies on the levels ‘below’ should be evaluated, as their relevance may change when these strategies are applied.

Circular Strategies Scanner - v1.0

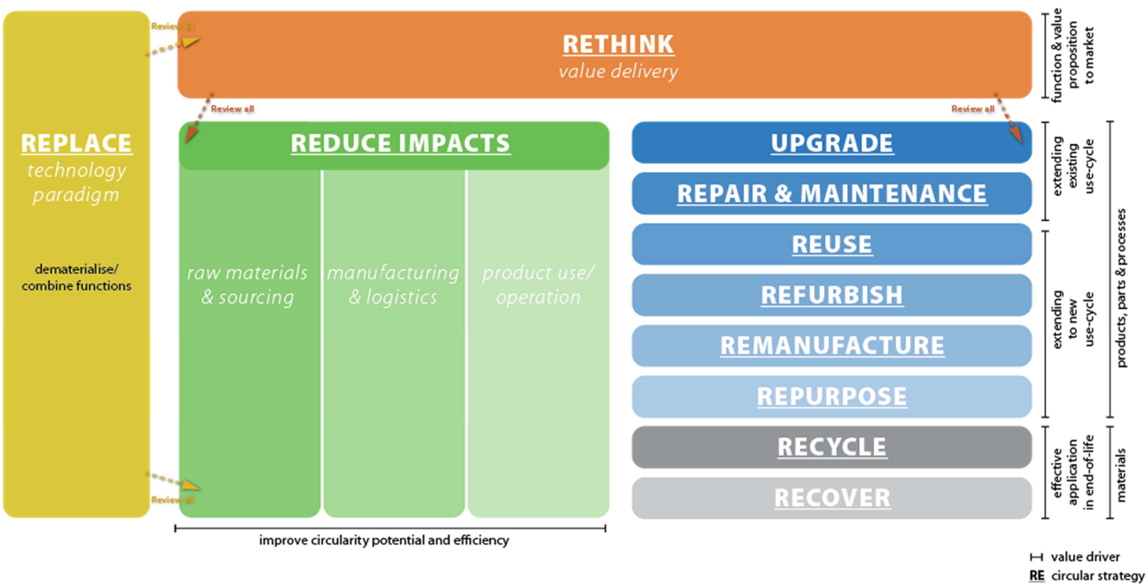


Figure 3 - The first version of the Circular Strategies Scanner.

Examples of other relationships include trade-offs: the choice, for instance, for certain durable materials such as composites may impede recycling. In this case, a strategy that facilitates product longevity, conflicts with recycling the material at the end-of-life. On the other hand, certain interventions may cause cumulative or

reinforcing effects, such as choosing a renewable material that at the end-of-life can be safely composted, allowing this single intervention to cover two circular strategies synergistically; the sourcing of materials that can be renewed and the 'recovery' of nutrients at the end-of-life. For this reason, the strategies that reduce impacts and that affect end-of-use/ life are placed on the same 'level.' When considering these strategies, therefore, it should be examined if trade-offs and/ or synergies with other strategies on this level exist.

With this structure the new framework departs from the hierarchy that Potting and colleagues use. However, the value drivers have been preserved and further refined, in line with the different business processes (see Medium adaptations 2 and 3).

6. Descriptive Study II

In this phase the framework was tested in workshops within three manufacturing businesses from the heavy machinery, electronics and furniture sectors. The aim was to gain insight into additional strategies to be added, as well as into refinements with regards to the placement of strategies. Moreover, this section provides an example with regards to how a circular strategies framework can be used in the early stage of COI.

6.1. Use of the new framework in workshops in Descriptive Study II

With each business a two-part workshop was carried out. The first part mapped the circular strategies currently applied within a product or service (category). Participants were asked to prepare by classifying their offering (products, services or PSS), and to identify and describe the strategies currently applied. In the workshop, all strategies were mapped onto the Scanner and discussed: the current implementation level of the strategies, as well as their respective affinities to the business and their resource efficiency impact (e.g.: percentage of total sales or revenues, percentage of sold products recovered for end-of-use/life treatment). The second part of the workshop focused on scanning for new opportunities to enhance or append additional strategies, through the evaluation of the current state and the identification of gaps and improvement hot spots. Case examples of other companies employing strategies across the full range of strategies covered by the Scanner were used to stimulate the discussion with participants.

In total, each workshop lasted approximately six hours and involved participants with diverse skills and expertise, such as marketing and sales, services and product development, after sales and customer services, operations, corporate social responsibility, IT, business strategy and finance. Moreover, representatives from the business leadership or top management participated in all workshops. The number of participants varied from three to ten, according to the business size.

6.2. Outcomes Descriptive Study II

An example of the mappings created in both phases of the workshop can be found in Figure 4. The top part represents individual initiatives currently applied by one of the companies (one initiative per number). This represents current CE initiatives or current capabilities that can contribute towards increased circularity. The bottom represents improvement areas: circular strategies that could be improved or scaled up, or strategies that could feasibly be added. Comparing the current state with new opportunities, it can be seen that ideas were generated that increased the coverage of circular strategies, some even developing into more advanced concepts when synergies between circular strategies were identified.

During the workshops with the companies, the framework functioned as a boundary object (Star and Griesemer, 1989) for different participants to align their perceptions. That is: clarifying the current state together allowed participants to build a common picture of their organisations' ongoing CE initiatives and current capabilities, and to align their understanding of their nature and maturity. Moreover, the shared

exploration of new opportunities helped the participants to share their perceptions of these opportunities, and set priorities for their innovation pipeline. In all cases the visioning exercise helped to identify why and where to focus, whether in relation to the development of circular business models, applying circular product design principles, the application of smart technologies, the assessment of potential initiatives in relation to their sustainability impact and/ or areas where collaboration with other stakeholders needed to be sought[4]. As such, this visioning exercise facilitated with the Scanner served to guide and direct the COI process to relevant initiatives and appropriately set the scope for these efforts early on. Direct feedback provided by individual participants supports this. Representative responses were "quite helpful", "great tools" and "visualization with the boards helped the conversation a lot."

However, observations were made that were used to improve the framework further. First, it was noted that efficient logistics is relevant throughout a product's life, and not just before, during and after manufacturing. That is: for operations extending existing life cycles or those that extend the product life to new use-cycles and in recovering materials for end-of-life treatment, logistics must be cost- and carbon efficient. It should be placed in such a way to indicate this broader relevance.

Moreover, it was observed that it is also possible to use the sourcing stage as an opportunity to recapture waste that has already entered the environment. The various projects around recovering plastic from the oceans are examples of this (The Ocean Cleanup 2018, Plastic Oceans 2018), and the framework should also highlight the possibility of sourcing such materials. These observations led to the Medium adaptations 1 and 2 discussed in the next section, see also Appendix C.

[4] For more on this, see the CIRCit website (circitnord.com).

Mapping of current and possible company strategies using Circular Strategies Scanner v1.0

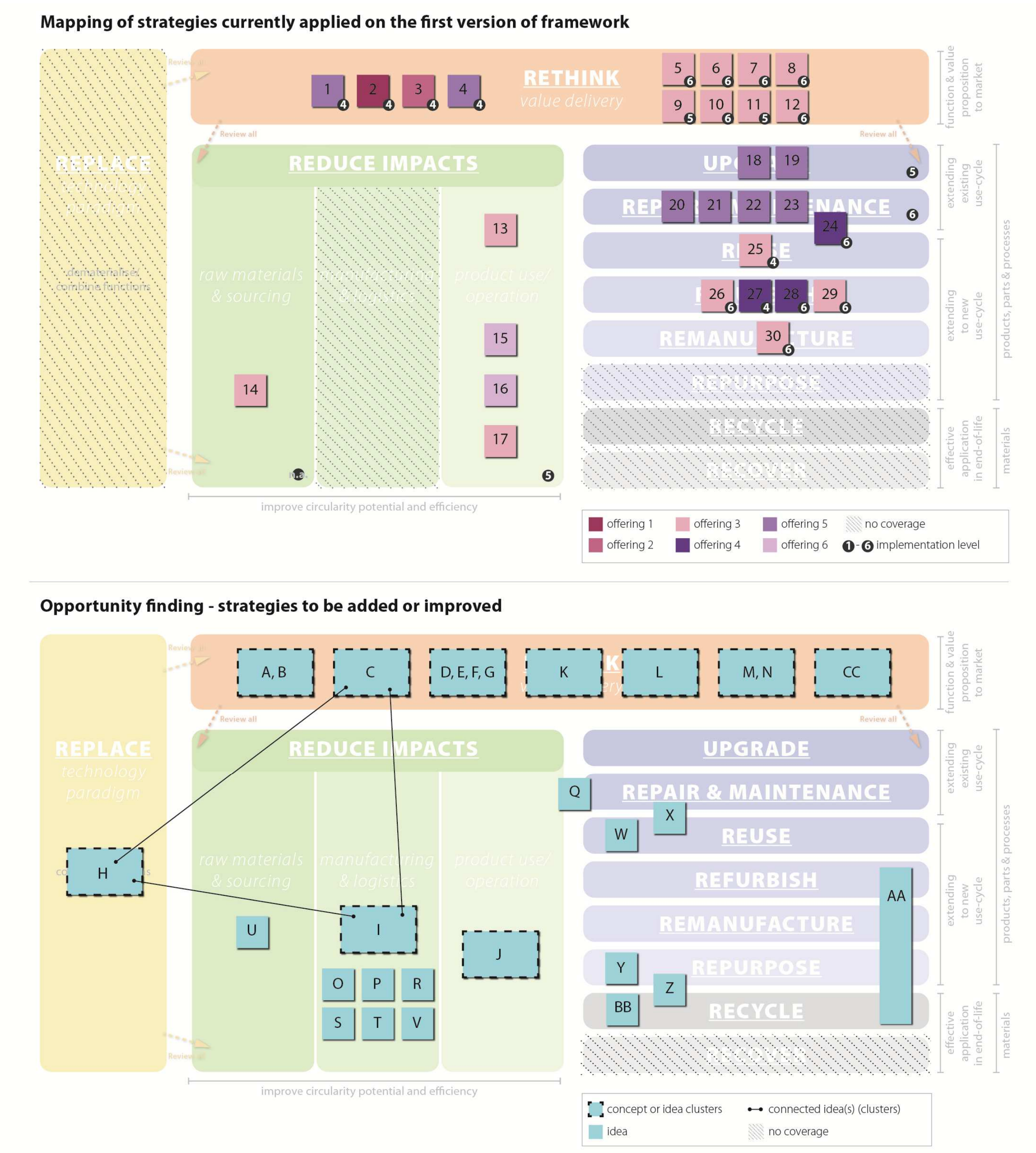


Figure 4 - Example of how the first version of the Circular Strategies Scanner was used in a two-part workshop with one of the companies participating in the CIRCit project. One or double letters are used per strategy: connected or grouped ideas represent closely related ideas that together constitute a new concept. Results are anonymised for reasons of confidentiality.

7. Prescriptive study II

The aim of this phase was to develop a second version of the framework on the basis of the identified improvement opportunities. The main activities were ongoing development efforts, supplemented by a series of meetings held to discuss the implementation of the suggested changes stemming from *Descriptive Study II* and the continued iteration of the *Research Clarification* and *Descriptive Study I.*

7.1. Outcomes Prescriptive Study II

No major adaptations were made, therefore the focus here is on medium adaptations: see for the second version of the framework Figure 5 and the complete set of changes Appendix B. See for definitions of individual strategies Table 2.

'Logistics' was assigned a separate layer such that it encompasses all the operational process areas. In addition to this and in a response to additional sources considered, 'Energy' was added as a layer encompassing all circular strategies (Cullen, 2017; Mestre and Cooper, 2017). That is: circular strategies should be considered with the intent to reduce overall energy consumption, and the use of clean(er) and renewable sources wherever possible.

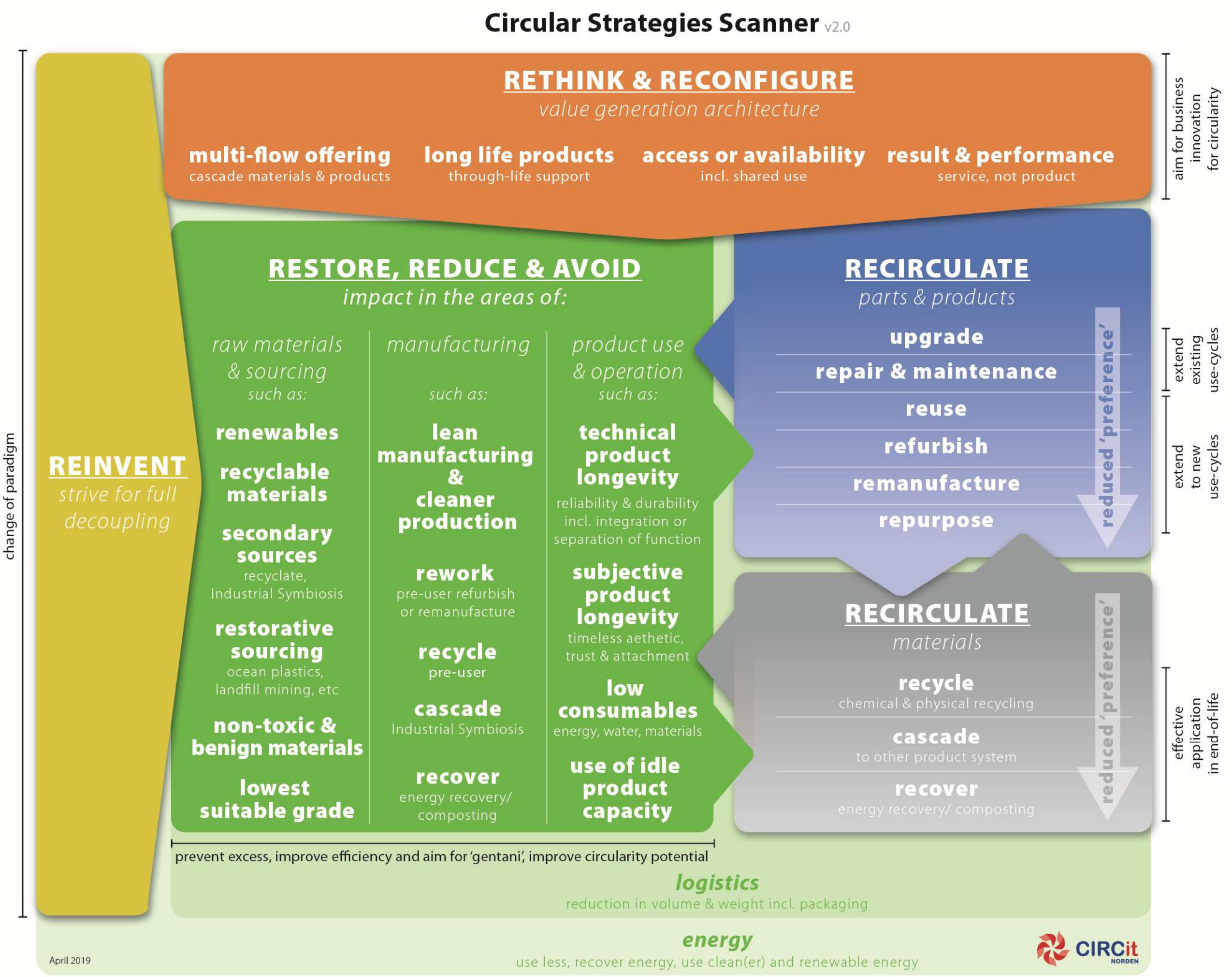


Figure 5 - The second version of the Circular Strategies Scanner.

Moreover, the heading 'Reduce impacts' was changed to 'Restore, reduce & avoid' to more fully reflect the range of strategies relevant for raw materials and sourcing, manufacturing, and product use and operation.

Also, more detail was added to the visual representation of the framework, which entailed the addition of suggested strategies in this area (see Minor adaptation 2). These strategies are meant to be inspirational, rather than exhaustive. In some cases this resulted in allocating strategies to multiple places in the framework, which is in line with Potting et al. (2017) and Reike et al. (2018). Recycling, for instance, can be found in both the category Restore, Reduce and Avoid, as well as in the category Recirculate - Materials. This reflects the fact that pre- and post consumer recycling can take place. Similarly, cascading, or industrial symbiosis can take a variety of different forms: as a sourcing strategy, as a way of valorise manufacturing waste, but also as an end-of-life strategy for materials. These multiple occurrences are also due to departing from the hierarchical structure used by Potting et al. (2017) (see also section *5. Prescriptive Study I*). For clarity descriptors have been added to signal the specific application of a strategy (see Minor adaptation 3).

Similarly, detail was added to the Rethink & Reconfigure category to clarify the framework's relationship with business models aspects. Two sources were consulted for this: Bocken et al. (2016) and Tukker (2004), chosen because of their seminal importance in the CE field (Pieroni et al. 2019) These respective typologies were synthesised into four main categories that cover circular business model strategies available to manufacturers and that represent a fundamental change to the logic of how such a business operates: 'Multi-flow offering,' 'Long-life products,' 'Access or availability,' and 'Result and performance.' This, as opposed to including strategies that are more appropriately thought of as supporting operational strategies such as efficiency and encouraging sufficiency.

Strategies included in the Circular Strategies Scanner (further developed from Potting et al. 2017)		
Driver	**Strategy** Synonyms	**Area of application or sub category** **Recirculation strategy** & synonyms ***Definition*** *(specifics)* • **Example practice(s)/ specifics**
Enable smarter business concepts through striving for full decoupling.	**Reinvent** Refuse	**The paradigm**
		Make physical products redundant by offering the same function or combined functions, usually enabled by radically different product, technology or both (Potting et al. 2017).
		• The 'bring-your-own' movement facilitates replacing such single use items such as coffee cups. • Music and video streaming services negate the need for data carriers such as CDs and DVDs. • Multi-functional devices such as smart phones combine the functionality of multiple devices (camera, GPS, phone, calculator, alarm clock, sound system, computer) in a single device.
Enable smarter business concepts through business model innovation for circularity. Products tend to not radically change, although the technology can evolve.	**Rethink & reconfigure** Revolution Replace	**Business models**
		Multi-flow offering – cascade materials, parts & products
		Extend the life of materials or products in a manner that exploits their residual value and becomes a significant part of the offering of the business. May involve providing new forms of value (Bocken et al., 2016).
		• Leesmap (magazine subscription where the price decreases with the age of the magazines). • British Sugar (from the core-business of sugar, to also selling many different co-products).
		Long life products – through- life support
		Extend the life of products through offering support during their lifetime (Tukker, 2004).
		• Provision of maintenance, offering of repair services, or sales of spare parts.
		Access or availability – incl. shared use
		Satisfying user needs without transferring ownership of physical products. Instead, user or consumer pays for access to the product for a certain period of time (Tukker, 2004).
		• Bike or car sharing services (e.g. Bycyklen in Copenhagen, Santander Cycles in London, and many other cities around the world; Drive Now, Green Mobility, Zipcar, Blablacar). • Clothing rental and subscriptions (e.g. Rent the Runway, Vigga, Mud Jeans).
		Result & performance – service, not product
		The provider of the service delivers an outcome for the customer (Tukker, 2004).
		• Performance contracts (Rolls Royce - Power by the Hour).
Prevent excess, improve efficiency and aim for 'gentani', improve circularity potential.	**Restore, reduce & avoid**	**Raw materials & sourcing**
		Improve circularity potential and efficiency in the sourcing process (Mestre and Cooper, 2017).
		• Sourcing of renewables. • Sourcing of recyclable materials. • Secondary sources (recycled materials, Industrial Symbiosis, other cascades). • Restorative sourcing (Use former 'wastes' as input: Landfill re-mining or using ocean plastics). • Use of non-toxic or benign materials (to facilitate re-absorption in natural cycles). • Use the lowest suitable grade of materials suitable (Reserve the highest-quality resources for the most demanding task, and use used resources further down the chain).
		Manufacturing
		Improve circularity potential and process efficiency in product manufacture through consuming fewer natural resources or energy, aim for 'gentani' (the absolute minimum input required to run a process) (Potting et al., 2017).
		• Lean manufacturing & cleaner production (use less energy and materials, treat wastes, etc). • Rework (pre-user refurbishment or remanufacture). • Recycle (pre-user recycling). • Cascade (find uses for manufacturing waste: internally/ at other facilities (Industrial Symbiosis)). • Recover (energy recovery, or recovery of biological nutrients).
		Product use & operation
		Improve circularity potential and efficiency in product use and operation through wiser use and operation of products (usually enabled by digital technologies), and aim for 'gentani' (the absolute minimum input required to run a process) (Potting et al., 2017; Reike et al., 2018).
		• Enable product longevity through high product integrity and robustness. • Use idle product capacity (historical usage data can be used for improvements such as better scheduling (of downtime), and (give insight into the possibilities for) pooled or shared use). • Low consumables of energy, water and materials during product use and operation.
		Logistics
		Improve process efficiency in logistics operations, aim for 'gentani' (minimum input into a process (Greenbiz, 2014)
		• Combine forward & return logistics. • Incentivize eco-friendly driving and transport. • Minimize, reuse or recycle (transit) packaging.
		Energy

		Improve energy efficiency and use clean(er) sources of energy (Cullen, 2017; Mestre and Cooper, 2017). • Use less energy • Renewable energy

Strategies included in the Circular Strategies Scanner *(cont).*		
Driver	**Strategy**	**Area of application or sub category** **Recirculation strategy** & synonyms ***Definition*** *(specifics)* • **Example practice(s)/ specifics**
Extend existing use cycles with the purpose of capturing (residual) value or to reduce value loss from continued use of parts and products	**Recirculate**	**Parts & products**
		Upgrade – Update, modernize, renew, retrofit, rebuild, overhaul, revive.
		Extend existing use cycle by adding value or enhancing the function of a product in respect to previous versions (Parkinson and Thompson, 2003; Potting et al., 2017).
		• Aesthetic upgrades (i.e. changing the coat or sleeve of a product due to a new preference). • Functional upgrades (i.e. software upgrades, hardware upgrades).
		Repair & maintenance – Corrective, condition based, predictive and prescriptive maintenance
		Extend existing use cycle by countering wear and tear, and correcting faulty components of a defective product/part to return it to its original functionality. ((Partial) disassembly envisioned, limited warranty may be issued). (Thierry et al, 1995; Stahel, 2006).
		• Providing a product with a service, which may involve the lubrication of critical parts, checking fasteners, the tension of chains and cables, the replacement of worn-out parts, etc. • Repair may involve the restoration or replacement of faulty parts and components.
Extend to new use cycles with the purpose of capturing (residual) value or to reduce value loss from continued use of parts and products.		Reuse – As-is reuse, redistribution, product cascading, minimise.
		Extend to new use cycle by reusing a part/ product (discarded/ not in use) that is still in good condition and can fulfil its original function in a different use context (new customer/user). (May involve a minimum amount of condition monitoring such as cleaning or repackaging. No warranties are provided and no disassembly is involved.) (Saavedra et al., 2013)
		• Selling used goods on platforms such as E-bay, • Return and resale of second hand goods through stores, such as Patagonia and Bergans. • The xStorage Home system (by Nissan and Eaton) gives old lithium-ion batteries from Nissan Leaf a second life inside of homes and businesses as backup and solar storage batteries.
		Refurbish – Recondition, retrofit, refresh, remodel.
		Extend to new use cycles by returning a part/ product (discarded/ not in use) to a satisfactory working condition that may be inferior to the original specification. (This may involve: cleaning, repairing, resurfacing, repainting, re-sleeving. Partial disassembly envisioned'. In the case of traditional product sales, a warranty for all major parts may be issued (less than the newly manufactured equivalent)). (Ijomah, 2002, 2009; Saavedra et al., 2013).
		• For example: taking in relatively modern, but disused white goods and performing repairs and/ or replacing lost parts and finding new users for the refurbished products (e.g. Norsk Omburk).
		Remanufacture – Rebuild, overhaul, remake.
		Extend to new use cycles by returning a product (discarded/ not in use) to at least Original Equipment Manufacturer (OEM) performance specification and quality. (Usually more rigorous and costly than refurbishment and involves total disassembly and reassembly. In the case of traditional product sales, a warranty that is at least equal to that of a newly manufactured equivalent may be issued). (Ijomah, 2002, 2009; Saavedra et al., 2013).
		• Renault engine blocks
		Repurpose – Alternate use.
		Extend to new use cycles by using a product (discarded/not in use) or its parts for different functions (Potting et al., 2017; Reike et al., 2018).
		• Mærsk providing containers to fit housing purposes in Copenhagen Village. • Using product packaging as storage or glassware (Nutella, Douwe Egberts).
Effective application in end-of-life of materials with the purpose of capturing (residual) value or to reduce value loss from continued use of materials.	**Recirculate**	**Materials**
		Recycle
		Extend material lifespan by processing them in order to obtain the same or comparable quality (Allwood et al., 2011).
		• Can-to-can recycling in beverage cans. • Chemical recycling of nylon.
		Cascade – Downcycling, upcycling.
		A subsequent use that significantly transforms the chemical or physical nature of the material (Sirkin and Ten Houten, 1994).
		• Repurposing of used clothing as an insulation material. • Used coffee grounds from coffee shops processed into biofuel, as medium for cultivation of edible mushrooms, for use in beauty products, etc.
		Recover
		Recover energy or nutrients from composting or processing materials. (Reike et al., 2018).
		• Incineration, pyrolysis or anaerobic digestion (recovery of energy). • Composting (recovery of biological nutrients).

Table 2 - Overview of the definitions of the circular strategies as used in the Circular Strategies Scanner.

8. Discussion

The Circular Strategies Scanner illustrates how to support visioning in COI processes, through supporting the explication of CE, mapping current CE initiatives, and generating ideas for increased circularity. With this, the framework of Potting et al. (2017) was significantly improved upon for the manufacturing context, see Table 3.

Criteria **The new framework should:**	**Potting et al. (2017)**	**Circular Strategies Scanner - v2.0**	**Summary of improvements that were realised**
01) A tool for inspiring, motivating and aligning people.	++	+++	*Improved capacity to serve as a boundary object where stakeholders can clearly identify their (influence on) activities, and see the applicability and relevance of circular strategies (see also the criteria below).*
02a) Balance the generation of new ideas, with that of describing existing situation.	++	+++	*The Scanner can directly and without transformations be used as a tool for mapping the circular strategies that are present in a situation, as well as for exploring what strategies can be improved or added (see section 6).*
02b) Provide an overview of the spectrum of available strategies ranging from incremental to transformative.	++	+++	*The Scanner groups circular strategies according to their potential for change in circularity levels. Strategies that can be thought of as having potential for incremental change are grouped under* Restore, reduce & avoid*; strategies that aim for higher levels of circularity through business model innovation are grouped in* Rethink & reconfigure*; and strategies that radically transform both business and user practices and achieve radical decoupling are placed in* Reinvent*.*
03) Indicate which strategies affect which business processes and related capabilities.	+	++	*The circular strategies in the Scanner are organised according to the business processes they apply to.* Reinvent *and* Rethink & reconfigure *represent groups that affect business strategy, and the remaining groups respectively affect operational processes, ranging from raw materials and sourcing, manufacturing, product use and operation, to the recirculation of parts and products, and materials.*
04a) Explicitly include the reduction and avoidance of resource use and impacts, as well as resource productivity strategies aimed at continued use and value delivery.	++	+++	*The Scanner covers a wider range of circular strategies, giving a more comprehensive overview of circular strategies that aim for the reduction and avoidance of resource use and impacts, as well as those that improve resource productivity strategies.*
04b) Allow for generating insight into circular configurations.	++	+++	*The Scanner implements a means of systematically exploring connections between circular strategies, through organising them in three 'levels' that indicate their relationship. This relationship can be bi-directional: e.g. a change in circular strategies in* Restore, reduce & avoid *may impact the circular strategies in* Recirculate and vice-versa*; or it may may be a unidirectional relationship where a change in* Reinvent *requires the reexamination of the relevance of circular strategies in* Rethink & reconfigure*, or where a change in* Rethink & reconfigure *requires a reconsideration of the strategies applied in* Restore, reduce & avoid.
05) Has to point to the value drivers that circular strategies can contribute to.	++	+++	*Each group of circular strategies in the Scanner is clearly linked to a value driver that aids its users in identifying relevant contributions to value creation and capture, such as improved efficiencies, supporting optimal use during the use phase, and value recovery opportunities, pointing to opportunities for either financial or non-financial gains within or outside the company.*
+++ = framework satisfies criterion very strongly, ++ = framework satisfies criterion strongly, + = framework satisfies criterion moderately, 0 = framework doesn't meet criterion or only marginally.			

Table 3 - Overview of the the improvements that the new framework makes in relation to the framework by Potting et al. (2017) that was used as a basis for its development.

A strength of using the Scanner in COI is that it provides a way of systematically exploring circular strategies. It thus provides guidance in identifying what business areas eco-innovation for CE is possible or necessary. For instance, when improved recycling is identified as an opportunity, the Scanner indicates that other circular strategies in the operational areas of raw materials and sourcing, manufacturing, product use and operation, and the recirculation of parts and products may be affected. Such impacts may be synergistic and result in increased overall circularity (e.g. the choice to change to a recyclable material to enable end-of-life recycling also enables recycling of waste within the manufacturing process), or they may take the form of trade-offs and require additional management or development for resolving them (e.g. changing to a recyclable material negatively affects the technical longevity of a product). Further work could focus on providing additional guidance with regards to how to systematically identify synergies and trade-offs.

Application of the Scanner furthermore strengthens the connection between eco-innovation and CE, by linking it with transformative innovation (De Jesus et al. 2018). It does this in two ways in COI processes. First, due to possibilities uncovered in the operational area, it can trigger a re-evaluation of the value generation architecture. Second, when the value generation architecture is the starting point, the Scanner indicates that the role of the circular strategies on the operational level need to be revisited as their relevance may increase or diminish depending on the context. In both cases, the Scanner invites a reconsideration of the system the manufacturing company is attempting to transform and links circular strategies together in circular configurations: situations where two or more circular strategies work together (Blomsma et al., 2018).

The range of sectors used for the validation efforts - heavy machinery, electronics and furniture - points to the broad applicability of the Scanner for manufacturing companies from different sectors. However, the framework could be further strengthened by validation with a wider set of manufacturing companies, including those that (also) operate within the biocycle, or that provide dissipative products (e.g. paints, lubricants, cleaning agents and other chemicals).

Further work should address how the Scanner can be linked to the assessment of (combinations of) circular strategies and different implementation scenarios, such that in the early stages of innovation processes the impact on economic, environmental and social systems can be evaluated and actions implemented to minimise negative impact and maximise positive impact. It could furthermore be explored whether the framework has potential to address the lack of a common understanding between value chain actors, which is perceived as an obstacle for the implementation of CE (Machacek et al. 2017; Lapko et al. 2018). In addition to using the Scanner by itself, there is also a need for understanding how different classes of circular strategies frameworks (e.g. macro, meso, micro, nano, networked) can best be used together.

9. Summary and conclusion

With this paper, we have contributed to the development of support tools for CE oriented innovation, or COI and to enable the translation of the CE concept in practice by creating support for visioning for CE. The contribution of this paper is four-fold: a) it provides an example of a process of how a circular strategies framework can be developed for a specific business type with the ability to support COI processes, b) it proposes a circular strategies framework for the manufacturing context, with c) an accompanying set of definitions of circular strategies, and d) it provides an example of how such a framework can be used in the early stages of a COI process. Next, it will be discussed how each goal was achieved and what the implications are for academia and industry.

In support of the first goal - to provide an example of the development of a circular strategies framework - this paper used the lens of Design Research Methodology (Blessing and Chakrabarti, 2009). This answered the call for the more deliberate and systematic development of circular strategies frameworks that are fit for purpose, voiced in Niero and Hauschild (2017) and Blomsma (2018). With manufacturing companies as the focus, it provided an example of how academia and industry can work together following a transdisciplinary approach (Sakao and Brambila, 2018) in developing resonant frameworks for specific audiences. The systematic development approach followed in this paper can be adapted and further expanded upon for other business types or other innovation contexts.

The second goal was achieved through the provision of the Circular Strategies Scanner. This framework can be used as a tool in COI and provides practitioners in manufacturing with a way of contextualising the CE concept, mapping current CE initiatives, and generating ideas for increased circularity. The third contribution, the set of circular strategies definitions included in the framework, served to support the consolidation of CE terminology and bringing academic and practitioner terminology closer together (Reike et al. 2018; Meste and

Cooper 2017; Kalmykova et al., 2018). This was achieved through drawing on both academic and practitioner perspectives with regards to these definitions in the development process. Together, these two points mean that an important iteration on the framework provided by Potting and colleagues was made, which brings more precision to the framework and which customises it for the manufacturing context. With this, the framework has been transformed from analytical framework into an innovation tool.

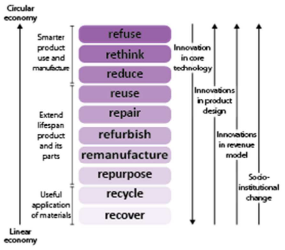
The fourth goal was achieved through illustrating how the Circular Strategies Scanner can be used in the early stages of a COI process to create a shared vision. The examples provided are of its application within businesses (see section 6). As well as with these companies, the Scanner was used with the other manufacturing companies participating in the CIRCit project. Specifically, it was used in the early stages of the action research, which allowed for a clear vision to be developed and establishing a clear direction for the work that followed, as it clarified with what aim different business activities relevant for COI needed to be deployed, whether this involved sustainability assessment, business model innovation, product design, digital technology strategies, the creation of take-back systems or value chain design.

Equally the Scanner could be applied across businesses, but also between business and academia, and beyond. In these contexts, the Scanner can serve as a boundary object where the stakeholders can clearly identify their activities or influence on different business processes across the life cycle, also enabling the comparison of CE initiatives and sharing of best practices.

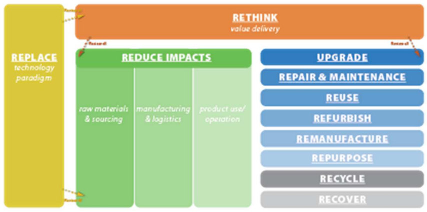
Acknowledgements
This article is one of the outcomes of the research project CIRCit (Circular Economy Integration in the Nordic Industry for Enhanced Sustainability and Competitiveness), which is part of the Nordic Green Growth Research and Innovation Programme (grant numbers: 83144) and funded by NordForsk, Nordic Energy Research, and Nordic Innovation. We would also like to thank the companies participating in the CIRCit project and the anonymous reviewers whose thoughtful feedback aided the development of this work.

Appendix A

Overview of changes to adapt the Potting et al (2017) framework for the manufacturing context



Adapted into:

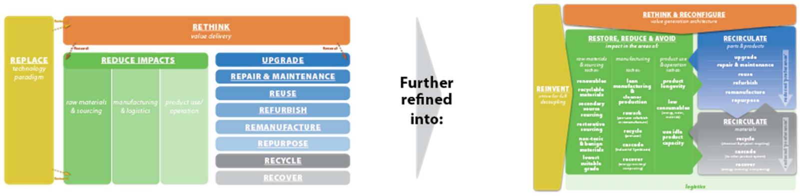


Major adaptations - changes in the structure of the framework		
#	In Potting et al (2017):	First version of Circular Strategies Scanner:
1	Circular strategies organised hierarchically: ranging from those that are considered more linear to those that are increasingly more circular.	Circular strategies are organised according to the business functions they apply to, in five main areas: *Replace*, *Rethink*, *Reduce Impacts* and two other operational process areas respectively containing end-of-use and end-of-life strategies
2	'Reduce' presented a single high-level strategy.	Specified into 'Reduce impacts' and the sub-categories of 'raw materials & sourcing,' 'manufacturing & logistics,' and 'product use/ operation.'
3	-	A visual structure consisting of three levels has been created to indicate the relationship of circular strategies, through the relative placement of the boxes containing the strategies, and the addition of arrows.
Medium adaptations - changes to the sub-groups or categories of the framework		
1	Inclusion of *Refuse* at the top of the hierarchy.	In the Circular Strategies Scanner, this strategy is understood as consisting of two sub-strategies and it was therefore split in two: *Refuse* (to abandon a practice altogether) and *Replace* (see Table 2). *Refuse* was subsequently not included in the framework, due to this framework targeting companies (see also Discussion section).
2	Contains the value driver: "Smarter product use and manufacture" for *Refuse*, *Rethink* and *Reduce*.	To refine this further, this value driver was split into "dematerialise/ combine functions" for *Replace*, "function & value proposition to market" for *Rethink*, and "improve circularity potential and efficiency" for *Reduce Impacts*.
3	Contains the value driver: "Extend lifespan of products and parts" for *Reuse*, *Repair*, *Refurbish*, *Remanufacture* and *Repurpose*.	To refine this further, this value driver was split in two to align with the end-of-use and end-of-life groupings as in line with Potting. As a result, *Upgrade*, *Repair & Maintenance* and *Reuse* are assigned the driver "Extending existing use-cycle," and *Refurbish*, *Remanufacture* and *Repurpose* are assigned the driver "Extending to new use-cycle."
Minor adaptations -- refinements in labels, definitions and the order of circular strategies		
1	Inclusion of *Recover*, as a strategy that refers to energy recovery through incineration, anaerobic digestion, pyrolysis.	The definition of *Recover* has been expanded to also include the recovery of biological nutrients and as such also covers such strategies as composting.
2	-	*Upgrade* was added to the framework to make explicit evolving quality and performance requirements of products.
3	*Reuse* comes before *Repair* in strategy order.	The order of *Reuse* and *Repair* was reversed, as Reuse that involves mere redistribution of products will – theoretically – maintain value to a higher degree with less added investment of resources, than redistribution that is also combined with repair activities.
4	Includes *Repair* as a circular strategy.	Repair was extended to also include maintenance, which is a common terminology in companies, and as such is indicated as *Repair & Maintenance* in the framework.

Table - This overview explains which changes were made to the Potting et al (2017) framework in order to adapt it to the manufacturing context. It gives a complete overview of the major, medium and minor adaptations.

Appendix B

Overview of changes to refine the 1st version of Circular Strategies Scanner and develop the 2nd version



Medium adaptations - changes to the sub-groups or categories of the framework

#	First version of framework	Second version of Circular Strategies Scanner:
1	The process of *Logistics* featured alongside *Manufacturing*.	*Logistics* is assigned a separate area in the framework, to better reflect that it covers all the operational process areas.
2	-	*Energy* was added as a relevant layer. That is: circular strategies should be considered with the intent to reduce overall energy consumption, and use clean(er) and renewable sources wherever possible.
3	Featured the strategy *Reduce Impacts*.	Label of strategy was changed to *Restore, Reduce and Avoid* to more fully reflect the range of strategies relevant for raw materials and sourcing, manufacturing and product use and operation.
4		Explicit addition of relevant strategies in *Restore, Reduce & Avoid.* Such as restorative sourcing (i.e. re-mining from landfill or using ocean plastics), lean and cleaner production practices and using idle product capacity. *Cascade* was also included: it can occur as Industrial Symbiosis and either as a secondary source sourcing strategy, or as a way of managing the co- and byproducts from manufacturing.
5	No detail provided regarding Rethink & Reconfigure.	To clarify the framework's relationship business models aspects, detail was added to the Rethink & Reconfigure category. This was done by drawing on Bocken et al. (2016) and Tukker's (2004) and adding the four main categories of Multi-flow offering, Long-life products, Access or availability, and Result and performance.
6	No explicit place for product and process design.	Product and process design are explicitly acknowledged by including them as box between Rethink & Reconfigure and the operational process of Restore, Reduce & Avoid and the Recirculate parts, products & materials.

Minor adaptations - refinements in labels, definitions and the order of circular strategies

#	First version of framework	Second version of Circular Strategies Scanner
1	Value drivers largely based on Potting et al. (2019).	Value drivers were further refined: for *Reinvent* it was changed to "strive for radical decoupling," and for *Rethink* to "aim for business innovation for circularity," and for *Restore, Reduce and Avoid,* to "prevent excess, improve efficiency and aim for 'gentani' and improve circularity potential."
2	Visual structure consisting of three levels has been created to indicate the relationship of circular strategies, through the relative placement of the boxes, and the addition of arrows.	Visual layering emphasised through depicting it using the visual metaphor of physical layers, which takes the form of drop shadows and arrows to indicate the relationship between the process areas. Hierarchical relationships indicated by a single arrow, trade-offs and synergies by bi-directional arrows.
3	No indication of hierarchy of end-of-use and end-of-life strategies	Arrows were added to indicate the (theoretically) preferred application order of these strategies.
4	Headings only applied for *Replace, Rethink* and *Reduce Impacts.*	For consistency, all five process areas are given headings. End-of-use processes are titled *Recirculate – parts & products* and end-of-life processes are titled *Recirculate – materials*.
5	-	*Cascade* was added to *Recirculate – materials*. This adds the distinction between recycling – i.e. those processes that keep material circulating at or near virgin levels of performance, and cascades – i.e. those processes that extend the life of materials through allowing for reduction or redefinition of performance characteristics.
6		Addition of descriptors to strategies to aid in clarifying the type of application. For example: recycling can take place at the manufacturing stage, where it involves re-entering waste from the manufacturing process back into the process: pre-user recycling. It can also take place post-user at the *Recirculate – materials* stage, in the form of chemical or physical (mechanical) recycling.
7	Featured the strategy label *Replace*.	*Replace* was changed to *Reinvent - strive for full decoupling*, to prevent confusion in relation the replacing harmful chemicals with less harmful or benign ones. Moreover, this term better conveys the transformative nature of this strategy.
8	Featured the strategy label *Rethink value delivery.*	Changed to *Rethink & Reconfigure value generation architecture.*

Table - This overview explains which changes were made to the first version of the framework in order to develop the second and final version. It gives a complete overview of the medium and minor adaptations. No major adaptations were made at this stage.

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Developing a circular strategies framework for manufacturing companies to support circular economy-oriented innovation

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Abstract

This paper puts forward the Circular Strategies Scanner: a framework that introduces a taxonomy of circular strategies developed for use by manufacturing companies engaging in circular economy (CE) oriented innovation. Currently, a range of frameworks exists that propose a vision for how to operate in a CE, by identifying and organising relevant circular strategies. However, these frameworks have a limited applicability for specific business types, in particular manufacturing, and are unsuitable for use in CE oriented innovation, due to a lacking ability to support innovation processes through: 1) creating a comprehensive understanding of circular strategies, 2) mapping strategies currently applied and 3) finding opportunities for improved circularity across a range of business processes. This paper addresses these shortcomings by proposing a circular strategies framework for the manufacturing context, titled the Circular Strategies Scanner, which provides a comprehensive set of definitions of circular strategies and directly supports the early stages of CE oriented innovation. With this, the paper contributes to the body of work that develops CE transition methodology.

Keywords Circular strategies framework, closed loop, resource productivity, manufacturing companies, innovation.

1. Introduction

The linear economy is frequently characterised by the presence of structural waste: instances where components, products or materials reach their end-of-use/life prematurely, or where their capacity for value creation is underutilised. To address this, the circular economy (CE) concept proposes a range of efficiency and productivity enhancing activities collectively known as circular strategies, such as reduce, reuse, repair, recycle, restore, cascading, etc (EMF, 2013). In this sense, CE is an umbrella concept: it groups a range of sub-concepts and imbues them with a new meaning by highlighting a shared feature of the sub-concepts (Blomsma and Brennan 2017). This new meaning revolves around the notion that through the application of circular strategies both more value can be created (EMF, 2013) as well as value loss and destruction reduced (Murray et al., 2015).

Although CE has widely been recognised as an idea with potential merit, it has yet to be widely implemented and embedded within business and industry (Haas et al., 2015; Circle Economy 2019). This is in line with the progression of umbrella concepts: when the transformative potential of an idea has been recognised, the attention then turns to operationalising it through frameworks, tools, methods and approaches. This, in turn, allows for further examination of the concept.

For CE this means that there is currently a focus on developing CE transition methodology. This is taking place in a number of aspects relevant for Circular Oriented Innovation (COI) (Brown et al. 2019), such as in business models (Bocken and Antikanen 2018; Pieroni et al. 2019; Rosa et al. 2019), metrics and assessment (Kravchenko et al. 2019; Moraga et al. 2019; Saidani et al. 2019), product design (Moreno et al. 2016; Den Hollander et al. 2017) and the creation of organisational capabilities such as experimentation, value chain innovation and other human factors (Weissbrod and Bocken 2017; Chiappetta Jabbour et al. 2019; Nilsson-Lindén et al. 2019).

Previous academic work focuses on answering 'what' or 'how' to promote COI (Guzzo et al. 2019; Mendoza et al. 2017). However, supporting the early stages of COI through the establishment of a CE vision, i.e. answering

why to perform COI, has so far achieved relatively little scholarly attention. Finding the 'why' for a CE transition, requires understanding the type of structural waste in the system, which can be accomplished with a systemic analysis/diagnosis across life cycle stages and various business processes and knowledge areas. This requires various actors within and across business to define and explore problem and solution spaces together (Brown et al., 2019). Specifically, in COI a high-level conceptual understanding of CE needs to be translated into a vision that is useful and meaningful on the level of decision making (Hoffman, 2003; Boons and Howard-Grenville, 2009; Lindkvist and Baumann, 2014). The importance of a shared vision in innovation projects has long since been acknowledged (Pearce and Ensley, 2004; Bititci et al., 2004), and it has been posited to be relevant for both inter and intra organisational COI efforts (Brown et al., 2019).

Currently, there exists a range of frameworks that could potentially be drawn from to support CE visioning. These take the form of circular strategies frameworks, such as the ReSOLVE framework (EMF, 2015), the Performance Economy (Stahel ,2006), Cradle-to-Cradle™ (Braungart and McDonough, 2002), and the Waste Hierarchy (EC, 2008), but also the Ricoh Comet Circle™ (Ricoh, 2018), the Seven Fronts of Mount Sustainability (Interface, 2018). Importantly, these frameworks can be seen as the visual representations of a vision for how to operate in a CE, since they select, name and organise circular strategies seen as relevant, such that their relationship becomes apparent.

However, Mendoza et al. (2017), Reike et al. (2017) and Blomsma (2018) observed that such circular strategies frameworks can identify or emphasise different (groups of) circular strategies, which can be linked to addressing different types of structural waste. As such, there is a risk that they do not include circular strategies with transformative potential for a particular context. Moreover, Blomsma (2018) points out that little work has been done with regard to ensuring that frameworks are seen as relevant and useful by their intended audiences. For these reasons, there is scope to further develop these frameworks to support visioning in COI. Mendoza et al. (2017), Niero and Hauschild (2017) and Blomsma (2018) therefore call for the development of such frameworks within academia.

This paper answers this call and addresses the question of how to develop circular strategies frameworks such that they are relevant for their intended audiences, in a manner that points to the transformative potential of CE and that assists with unpacking the complexity associated with COI. With this, this paper contributes to the body of work that develops CE transition methodology, focussing on the early stages of COI and engaging the affected audiences in a transdisciplinary approach (Sakao and Brambila, 2018).

As an illustrative case, we develop a circular strategies framework for manufacturing companies1. Manufacturing companies were chosen as the focus as they are important users of materials and energy, produce significant amounts of byproducts traditionally regarded as waste, and form an important employment sector2 and contributor to GDP (Rashid et al., 2013). In addition, manufacturing companies play an important role in the creation of value to their customers and therefore have great potential to decouple this value provision from linear resource consumption.

After clarifying the research gap in the background section and exploring the shortfalls of current circular strategies frameworks to support COI within manufacturing, we continue with setting out the methodology applied in this paper. In the following sections we present the development of the criteria used for designing the new framework and explain the relevant details and outcomes of each subsequent development phase. Furthermore, in section 6, we provide an example of application of the framework in COI. We close with a discussion of the contributions of this paper and directions for further work.

[1] We use the expression *manufacturing companies* to refer to secondary manufacturing, as opposed to primary production. Moreover, these companies are not contract manufacturers, but have a degree of control over their supply chain.

[2] Sector, as used here, refers to an area of economic activity such as food, medicine, construction, etc. See: https://unstats.un.org/unsd/classifications/.

2. Background and research clarification

Describing the complete landscape of circular strategies frameworks is beyond the scope of this paper. However, here we provide an overview of the current landscape of circular strategies framework, through offering a typology of five classes of frameworks. The first four classes describe a continuum where the scope becomes increasingly smaller: (1) the macro level of industrial systems or economies; (2) the meso level of sectors, materials and business types; (3) the micro level of companies; and (4) the nano level covering product (groups) (Saidani et al., 2017). The fifth level adds the layer of (5) networked and regional approaches, through which the other four levels are connected. See Figure 1.

Overview of the landscape of circular strategies frameworks

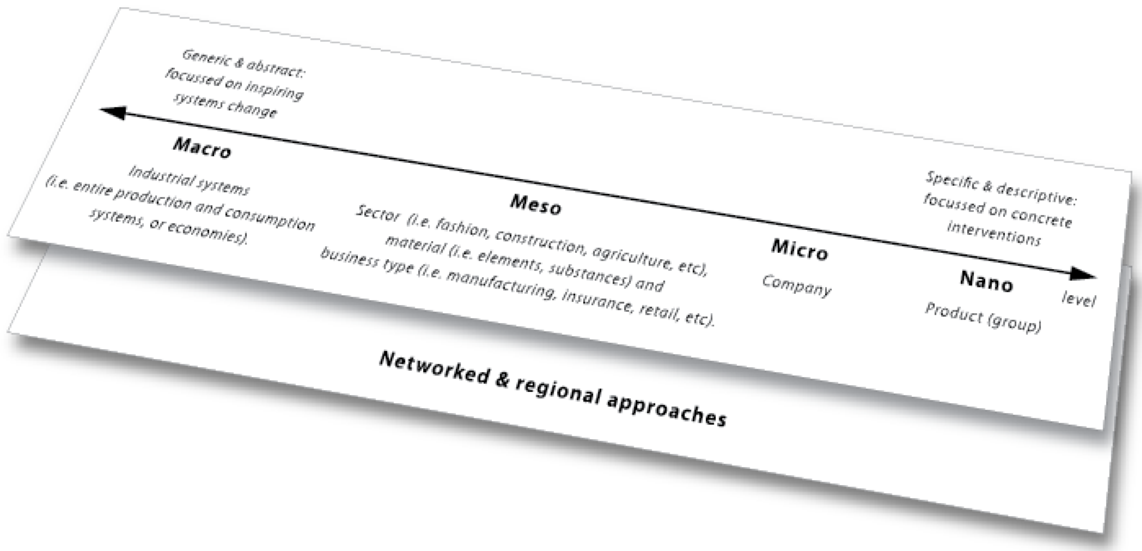


Figure 1. Schematic illustrating the coverage of frameworks on the macro-meso-micro-nano scale, and their relationship with frameworks covering networked and regional approaches.

Considering the landscape of current circular strategies frameworks, a number of observations can be made that explain why current circular strategies frameworks fall short in their capacity to support visioning for manufacturing. First, a circular strategies framework needs to create a comprehensive understanding of circular strategies, as relevant for the purpose (Brown et al., 2019) and context (Blomsma, 2018). Think, for instance, of the difference in the main functions of insurance and finance firms, retail and wholesale businesses, service providers, and manufacturing companies. Different circular strategies will be relevant in these contexts (Rashid et al. 2013; Johannsdottir 2014; Upadhyay et al., 2019).

Currently a multitude of frameworks exist on all levels of the landscape. See for frameworks on the macro level, for example: Allwood et al. (2011), Reike et al. (2018), Bocken et al. (2016), or Braungart and McDonough (2002). Likewise, for meso level frameworks for materials, see for water (WssTP, 2015) and biomass (ECN, 2018); or fashion and textile frameworks by EMF (2017), Inditex (2016) and Mistra Future Fashion (2018). On the micro level, consider: Gispen's (2018) framework for circular furniture, *The 10 R's of Circularity* by (Mitsubishi Electra, 2018), the Ricoh Comet Circle™ (Ricoh, 2018) (first used in 1994), or the framework used by Konecranes (2018). Likewise, on the nano level: Circular Jeans by Levi Strauss & Co. (2015), and Re-Entry for carpet tiles (Interface, 2016). Lastly, on the networked level, consider: Ehrenfeld and Gertler, 1997; Aguinaga et al., 2018; Pauli, 2010.

A notable exception of circular strategies frameworks exists on the meso level that apply to specific business types, in particular to manufacturing. One exception is the ResCom framework by Rashid et al. (2013), which targets manufacturing companies. However, this framework is also not well suited to supporting innovation processes, as it includes few circular strategies and contains a limited consideration of business processes.

In addition to creating a comprehensive understanding of circular strategies, a circular strategies framework that supports visioning needs to both map strategies currently applied as well as find opportunities for improved circularity for a range of business processes from a systemic point of view. In this aspect, current frameworks are also lacking as they are often derived or compiled to serve as a summary or overview of a piece of (mostly theoretical) work, as opposed to being purposefully developed for use in COI in and with businesses (Niero and Hauschild, 2017; Kalmykova et al., 2018; Blomsma, 2018; Sakao and Brambila, 2018). However, to establish a vision it is important to both understand the current situation - e.g. what is already being done towards CE, or what capabilities provide a basis for this, as well as to identify what opportunities are present and desirable. Current circular strategies frameworks are not designed to capture an overview of both the current situation and ideas for future innovation.

Another shortcoming of current circular strategy frameworks is that they exhibit ambiguity with regards to the meaning of and relationships between the included circular strategies, allowing the same term to adopt multiple meanings - sometimes with radically different outcomes from a resource perspective (e.g. whether recycling keeps material quality on a consistently high level, or whether it represents downcycling) - or to be rendered inapplicable to some contexts (Reike et al., 2018; Blomsma, 2018).

This paper addresses these shortcomings, by a) providing an example of a process of how a circular strategies framework can be developed for a specific business type with the ability to support COI processes, b) proposing a circular strategies framework for the manufacturing context, resulting in the Circular Strategies Scanner, with c) an accompanying set of definitions of circular strategies (including commonly used synonyms). In addition to this, we provide d) an example of how such a framework can be used to structure and guide the early phases of COI, in order to show the relevance of visioning approaches within CE transition methodology.

3. Methodology

Design Research Methodology (DRM) was applied for the development of the new circular strategies framework for manufacturing, as this method is particularly suited to the deliberate iteration of methods and tools (Blessing and Chakrabarti, 2009). Next, a high-level overview of the aim and activities in each phase is provided. See Figure 2 for an overview: more details are provided in the sections dedicated to each respective phase. The development of the proposed framework took place from November 2017 to July 2019.

Research clarification - This phase, already discussed in the previous section, served to refine the research gap and identify the need for a framework specifically for manufacturing companies.

Descriptive study I - This phase served three goals. First, a list of circular strategies to be included in the framework was compiled. Second, criteria that could be used to guide the development process of the new framework were articulated, which, third, were used to choose an existing framework as the basis for the development of the new framework. A series of workshops and meetings were held for this purpose. Iterations of the strategies list, their definitions and the framework requirements were performed throughout the project, but are presented as a single phase for clarity and brevity.

Prescriptive study I - A series of workshops and follow-up meetings were held to conceptualize and develop a first version of the circular strategies framework, as well as the corresponding clarifications and elaborations on strategies, and the relationship between them.

Descriptive Study II - In this phase the applicability and usefulness of the framework in the context of the manufacturing sector was evaluated and improvement opportunities sought. Workshops were performed with three manufacturing companies from the heavy machinery, electronics and furniture sector.

Prescriptive study II - A series of meetings was held to discuss the implementation of the improvement opportunities, based on insights from *Descriptive Study II* and the iterations of the *Research Clarification* and *Descriptive Study I* phases. A second version of the framework and a final list of strategies and their definitions were developed during this phase.

Moreover, the approach applied was deliberately transdisciplinary. That is, it aimed for establishing “a common system of axioms for a set of disciplines,” which was achieved in two ways (Sakao and Brambila-Macias, 2018:1400), see also Figure 2:

(1) *Adopting a systemic view* - In the context of (more) circular manufacturing this means the alignment of the different business processes, which together contribute to the creation of circular systems. The perspectives of these processes therefore need to be included.
(2) *Inclusion of non-academic stakeholders* - Creating (more) circular manufacturing systems entails affecting changes in manufacturing companies. As such, it is important to acknowledge the perspective of manufacturing companies in the development of the new framework.

The first type of transdisciplinarity was implemented through the creation of the CIRCit research consortium[3] to represent the knowledge related to business model strategy, product design, and a range of operational processes such as sourcing, manufacturing, logistics, through-life support, digital technologies and end-of-life operations, but also sustainability aspects and value chain management.

The second type of transdisciplinarity was implemented through application of the framework on retrospective company cases, as well as applying the framework in ongoing research that is actively supporting companies in implementing circular practices. Furthermore, the consortium contained representatives of the interests of manufacturing companies, such as industry associations. Through this, the perspective of ‘real-world’ considerations was added. Next, the outcomes of each phase is presented.

[3] See for more information about the consortium: www.circitnord.com.

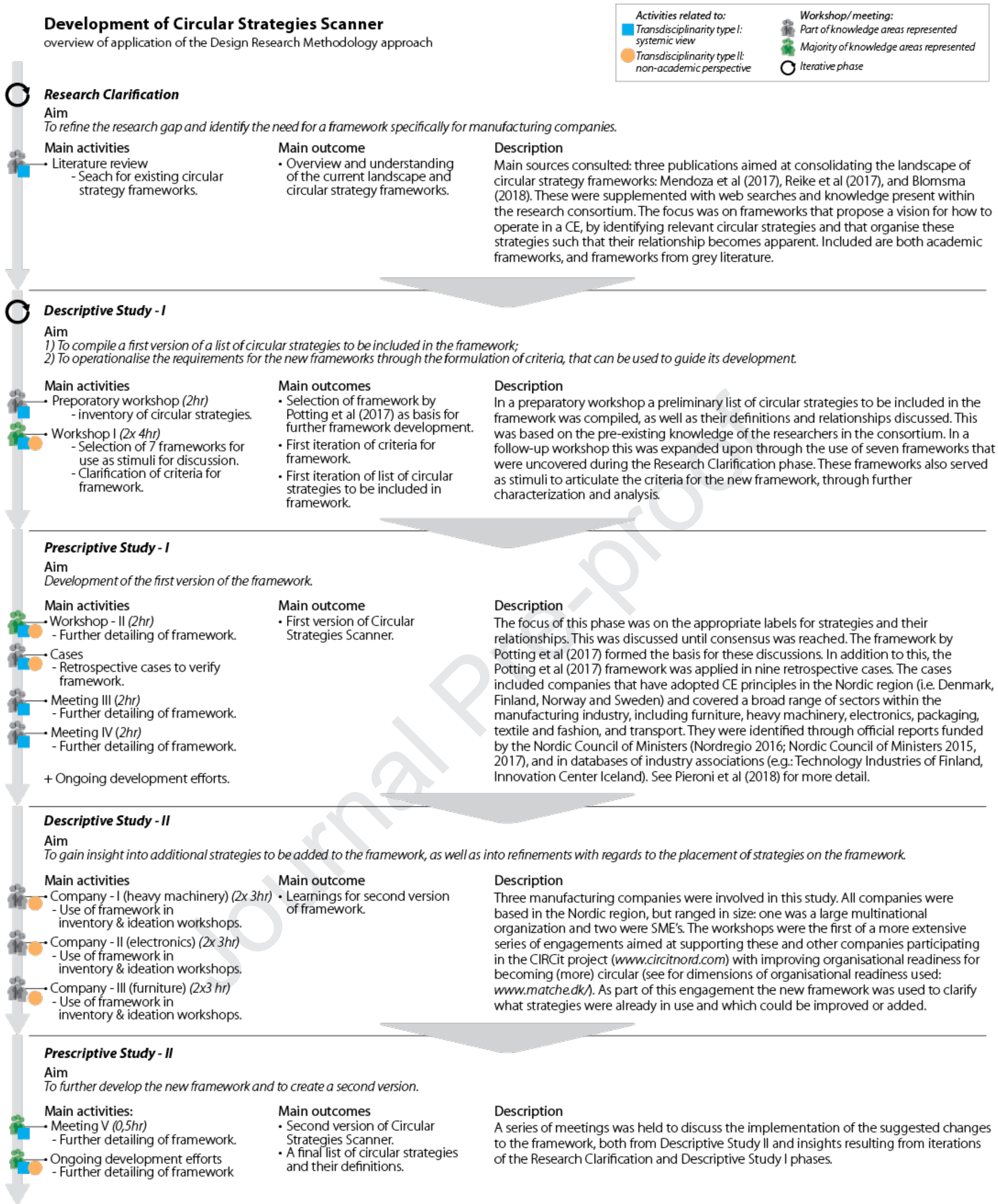


Figure 2. Schematic illustration of the approach followed for the development of the Circular Strategies Scanner.

4. Descriptive Study I - criteria for a circular strategies framework for manufacturing companies

This phase served to establish a foundation for the development of the new framework. This was done in the following manner, see also Figure 2.

4.1. Rationale behind Descriptive Study I

Due to the lack of suitable meso level frameworks with a business type orientation, macro frameworks were used as a starting point with the aim to adapt their generic applicability and generative capacity for manufacturing companies. From the macro frameworks 1) relevant circular strategies were extracted, and 2) criteria that could be used to guide the development process of the new framework were articulated, which 3) were used to choose the best fitting existing framework as the basis for the development of the new framework. In particular, seven macro level frameworks uncovered during the Research Clarification phase were used: Thierry et al. (1995), Parkinson and Thompson (2003), Allwood et al. (2011), Bocken et al. (2016), Nussholz (2017), Potting et al. (2017), and Blomsma (2018). These were included based on 1) their range of relevant strategies for the manufacturing context, 2) their inclusion of definitions and/or examples of these strategies and 3) representing a broad range of approaches to classify or organise the strategies in relation to each other. This served to have contrasting definitions and approaches that could be discussed and analysed.

4.2. Outcomes Descriptive Study I

The final version of the list of included strategies, their definitions and examples, which continued to be iterated throughout the development of the framework, can be found in Table 2 (see section 7. *Prescriptive study II*). Here, the focus is on the five criteria for the new framework that were developed to detail the main functions of a circular strategies framework (create understanding of CE, map current CE initiatives, generate ideas for increased circularity). The criteria were iterated until they represented five clear requirements for the development of the new framework. This section concludes with the selection of the best fitting existing framework.

Criterion #01: A tool for inspiring, motivating and aligning people

In innovation processes it is important to invoke relevant frames, acknowledge cognitive principles (which involve cognitive limits, but also principles of attention, inspiration and motivation) and, in collaborative settings, to consider the alignment of understanding, mindsets and interests between different stakeholders. Language, both visual and written, plays an important role in this: it helps directing attention, summarising and synthesising information from internal and external knowledge sources and it supports orientation towards relevant aspects of the context (Biloslavo et al., 2018; Breuer et al., 2018) and in the creation of a shared vision, also in the context of CE (Blomsma, 2018). Therefore, in line with the frameworks discussed above, the proposed framework should 01) represent a complex phenomenon in an easily accessible manner in order to inspire, motivate and align people.

Criterion #02: A tool for describing current situations and identifying opportunities, both incremental & transformative

A framework suitable for use by a wide variety of manufacturing businesses, cannot be broad in the sense of the frameworks on the macro level, as it will lose relevance. At the same time, it can also not be specific in the sense of the company and product frameworks, as this would mean it is limited in its reach and impact. However, the new framework should be suitable for describing both current initiatives and have the capacity to systematically explore relevant strategies and identify new opportunities. As such, the new framework should balance the strengths of the macro and meso level frameworks - which are generative and allow for the exploration of alternatives, with that of the micro and nano level frameworks - which offer greater specificity in relation to the context in which strategies are applied. Thus, the new framework should: 02a) balance the generation of new ideas, with that of describing existing situations. This indicates that it is preferable to include a diverse set of circular strategies, as opposed to high-level aggregated groups of strategies.

Furthermore, opportunity finding needs to point to the potential for improving existing strategies, as well as to radically different ways of achieving goals and creating, delivering and capturing value. This can involve the design, production and/ or transport of physical products, but it can also require a change in the business logic and operations that changes how products are commercialized and consumed. Think of the implementation of access-over-ownership models, or radical dematerialisation through a change in paradigm. As such, the framework should 02b) provide an overview of the spectrum of available strategies ranging from incremental to transformative. This indicates that the set of included strategies should cover strategic as well as operational business processes.

Criterion #03: A tool for facilitating alignment of changes in business processes and capabilities
Circular strategies frameworks aimed at specific business types need to provide insight into which business processes relevant for that business type need to be aligned. This means, following Allwood et al. (2011), Potting et al. (2017) and Reike et al. (2018), that the new framework should indicate which circular strategies may apply to which flows. In the manufacturing context, this implies 03) indicating which strategies affect which business processes and related capabilities.

Criterion #04: A tool for bringing together efficiency and effectiveness strategies, and strategy configurations
Following e.g. Pauli (2010), Stahel (2006), Potting et al. (2017), Reike et al. (2018) and EMF (2015), we adopt the view that both resource-efficiency and resource-effectiveness are important in the manufacturing context. The new framework therefore should: 04a) explicitly include the reduction and avoidance of resource use and impacts, as well as resource productivity strategies aimed at continued use and value delivery.

Moreover, many manufacturing companies operate in complex scenarios, that can be thought of as circular configurations: situations where two or more circular strategies are present (Blomsma and Brennan 2017, Blomsma 2018). Think of product/ service systems where direct reuse, but also repair, refurbishment and remanufacturing are taking place, in addition to the recycling of materials. As such, the proposed framework should: 04b) allow for generating insight into circular configurations.

Criterion #05: A tool for alignment with drivers: value creation & capture orientation
Businesses need to create and capture value to continue their activities. It is widely acknowledged that circular strategies have the capacity to contribute to this. However, not many current frameworks support the identification of the type of value that can be captured through which strategies. The new framework therefore needs to be aligned with the perspective of systemic value creation and capture. Support in identifying this can enable assessing and measuring outcomes and tracking potential deviations from the planned future state, which is fundamental to transition management (Breuer et al., 2018). As such, the proposed framework: 05) has to point to the value drivers that circular strategies can contribute to. That is: the framework has to help users identify relevant contributions to value creation and capture, such as improved efficiencies, supporting optimal use during the use phase, and value recovery opportunities, resulting in either financial or non-financial gains within or outside the company (Circle Economy et al., 2016). As these may be relevant for business shareholders, but also suppliers and customers, the environment and society they need to be formulated such that relevance for these stakeholders can be easily appreciated.

Next, the seven frameworks were compared and rated on these criteria, see Table 1. Although none have a perfect score, the framework by Potting et al. (2017) scores the highest: it represents a complex phenomenon in an easily accessible manner (criterion 01), contains a comprehensive set of circular strategies (criterion 02b), includes efficiency as well as effectiveness strategies (criterion 04a) and points to value drivers that circular strategies can contribute to (criterion 05). This framework was therefore chosen as a basis for further development of the new framework, with its relevance for different business processes and capabilities (criterion 03) identified as in need of further improvement.

Criteria The new framework should:	Bocken et al (2016)	Allwood et al (2011)	Parkinson & Thompson (2003)	Thierry et al (1995)	Potting et al (2017)	Nussholz (2017)	Blomsma (2018)
01) A tool for inspiring, motivating and aligning people.	+	++	0	++	++	+	+
02a) Balance the generation of new ideas, with that of describing existing situation.	0	+	0	+	++	+	0
02b) Provide an overview of the spectrum of available strategies ranging from incremental to transformative.	+	+	0	+	++	++	0
03) Indicate which strategies affect which business processes.	0	+	0	+	+	0	0
04a) Explicitly include the reduction and avoidance of resource use and impacts, as well as resource productivity strategies aimed at continued use and value delivery.	+	+	0	0	++	++	0
04b) Allow for generating insight into circular configurations.	+	++	0	++	++	+	+
05) Has to point to the value drivers that circular strategies can contribute to.	++	0	0	+	++	+	++
+++ = framework satisfies criterion very strongly, ++ = framework satisfies criterion strongly, + = framework satisfies criterion moderately, 0 = framework doesn't meet criterion or only marginally.							

Table 1 - Comparison of the seven frameworks that were used in Descriptive Study I using the development criteria.

5. Prescriptive Study I

During this phase the first version of the new framework was developed, through adding detail to Potting et al. (2017) as relevant for the manufacturing business type, guided by the criteria established in the above and the exploratory case studies (see Pieroni et al., 2018). The focus was on the appropriate labels for strategies, and how to convey the relationship between the included strategies.

5.1. Outcomes Prescriptive Study I

The outcomes of this phase is discussed in terms of the adaptations of the Potting et al. (2017) framework that were made. Only the major adaptations are elaborated upon: see for the first version of the framework Figure 3 and the complete set of changes Appendix A. See for definitions and examples of individual strategies Table 2 (section *7. Prescriptive study II*).

Major adaptations #01 and #02: Organisation of circular strategies according to business processes, and greater specificity for 'Reduce'

The preliminary list of circular strategies from the previous phase was organised according to the business processes as typically found in the manufacturing context, to meet criterion #03. For this, the process of transformation of raw materials into finished or intermediate goods was divided as follows. First, two areas that are related to the corporate strategy were identified: the first is changing the paradigm of practices and was named 'Replace,' and the second is a reconsideration of how value is delivered, entitled 'Rethink.' The former strategy enables radical dematerialisation through different ways of performing functions (e.g. functional replacement or new practices), which can be enabled by new technologies. This strategy was renamed from Potting and colleagues' 'Refuse' (see Medium adaptation 1 in Appendix A). The latter strategy involves new business models that are more resource efficient, such as access-over-ownership offerings, enabled by commercial models based on leasing, renting or pay-as-you-go. As such, 'Replace' concerns the

delivery of functionality through radically different means, whilst 'Rethink' delivers similar functionality through different customer relationships and which may involve a redefinition of the functional unit.

The remainder of the framework concerns operational processes. Potting et al's (2017) 'Reduce' was further divided to make its application to the following operational processes explicit: 'Raw materials and sourcing,' 'Manufacturing and logistics' and 'Product use/ operation.' This indicates that in these phases, the focus is on efficient use of resources and the reduction of harmful impacts.

The next two operational process areas respectively contain various end-of-use and end-of-life strategies. The first contains the strategies 'Upgrade' (see Minor adaptation 2), 'Repair & Maintenance' (see Minor adaptation 4), 'Reuse,' 'Refurbish,' 'Remanufacture,' and 'Repurpose'; and the second which contains the strategies 'Recycle' and 'Recover' (see Minor adaptation 1).

Major adaptation #03: Addition of the relationship between business processes
To capture the different relationships between the strategies (criterion 04b), a visual structure consisting of three levels has been created: the first occupied by 'Replace,' the second by 'Rethink' and the third by the remaining strategies. This is indicated by the relative placement of the boxes containing the strategies and the addition of arrows. This signals that, within the manufacturing context, some relationships between circular strategies are of a hierarchical nature, and some exist in the form of trade-offs and synergies. An example of a hierarchical relationship: 'Replace' may preclude the use of certain other circular strategies, when, for instance, a physical product is replaced by a virtual service. On the other hand, the application of 'Rethink' can require the support of repair and maintenance strategies to be viable, such as in certain product/service system offerings. As such, the application of either 'Replace' or 'Rethink' requires that the relevance of all strategies on the levels 'below' should be evaluated, as their relevance may change when these strategies are applied.

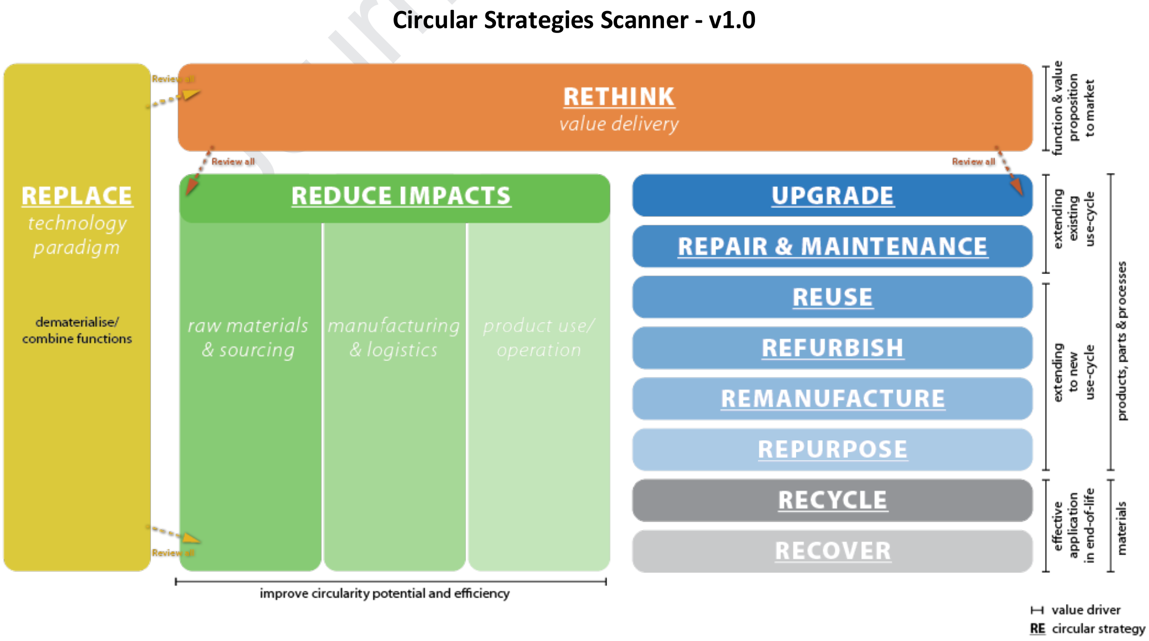


Figure 3 - The first version of the Circular Strategies Scanner.

Examples of other relationships include trade-offs: the choice, for instance, for certain durable materials such as composites may impede recycling. In this case, a strategy that facilitates product longevity, conflicts with recycling the material at the end-of-life. On the other hand, certain interventions may cause cumulative or

reinforcing effects, such as choosing a renewable material that at the end-of-life can be safely composted, allowing this single intervention to cover two circular strategies synergistically; the sourcing of materials that can be renewed and the 'recovery' of nutrients at the end-of-life. For this reason, the strategies that reduce impacts and that affect end-of-use/ life are placed on the same 'level.' When considering these strategies, therefore, it should be examined if trade-offs and/ or synergies with other strategies on this level exist.

With this structure the new framework departs from the hierarchy that Potting and colleagues use. However, the value drivers have been preserved and further refined, in line with the different business processes (see Medium adaptations 2 and 3).

6. Descriptive Study II

In this phase the framework was tested in workshops within three manufacturing businesses from the heavy machinery, electronics and furniture sectors. The aim was to gain insight into additional strategies to be added, as well as into refinements with regards to the placement of strategies. Moreover, this section provides an example with regards to how a circular strategies framework can be used in the early stage of COI.

6.1. Use of the new framework in workshops in Descriptive Study II

With each business a two-part workshop was carried out. The first part mapped the circular strategies currently applied within a product or service (category). Participants were asked to prepare by classifying their offering (products, services or PSS), and to identify and describe the strategies currently applied. In the workshop, all strategies were mapped onto the Scanner and discussed: the current implementation level of the strategies, as well as their respective affinities to the business and their resource efficiency impact (e.g.: percentage of total sales or revenues, percentage of sold products recovered for end-of-use/life treatment). The second part of the workshop focused on scanning for new opportunities to enhance or append additional strategies, through the evaluation of the current state and the identification of gaps and improvement hot spots. Case examples of other companies employing strategies across the full range of strategies covered by the Scanner were used to stimulate the discussion with participants.

In total, each workshop lasted approximately six hours and involved participants with diverse skills and expertise, such as marketing and sales, services and product development, after sales and customer services, operations, corporate social responsibility, IT, business strategy and finance. Moreover, representatives from the business leadership or top management participated in all workshops. The number of participants varied from three to ten, according to the business size.

6.2. Outcomes Descriptive Study II

An example of the mappings created in both phases of the workshop can be found in Figure 4. The top part represents individual initiatives currently applied by one of the companies (one initiative per number). This represents current CE initiatives or current capabilities that can contribute towards increased circularity. The bottom represents improvement areas: circular strategies that could be improved or scaled up, or strategies that could feasibly be added. Comparing the current state with new opportunities, it can be seen that ideas were generated that increased the coverage of circular strategies, some even developing into more advanced concepts when synergies between circular strategies were identified.

During the workshops with the companies, the framework functioned as a boundary object (Star and Griesemer, 1989) for different participants to align their perceptions. That is: clarifying the current state together allowed participants to build a common picture of their organisations' ongoing CE initiatives and current capabilities, and to align their understanding of their nature and maturity. Moreover, the shared

exploration of new opportunities helped the participants to share their perceptions of these opportunities, and set priorities for their innovation pipeline. In all cases the visioning exercise helped to identify why and where to focus, whether in relation to the development of circular business models, applying circular product design principles, the application of smart technologies, the assessment of potential initiatives in relation to their sustainability impact and/ or areas where collaboration with other stakeholders needed to be sought[4]. As such, this visioning exercise facilitated with the Scanner served to guide and direct the COI process to relevant initiatives and appropriately set the scope for these efforts early on. Direct feedback provided by individual participants supports this. Representative responses were “quite helpful”, “great tools” and “visualization with the boards helped the conversation a lot.”

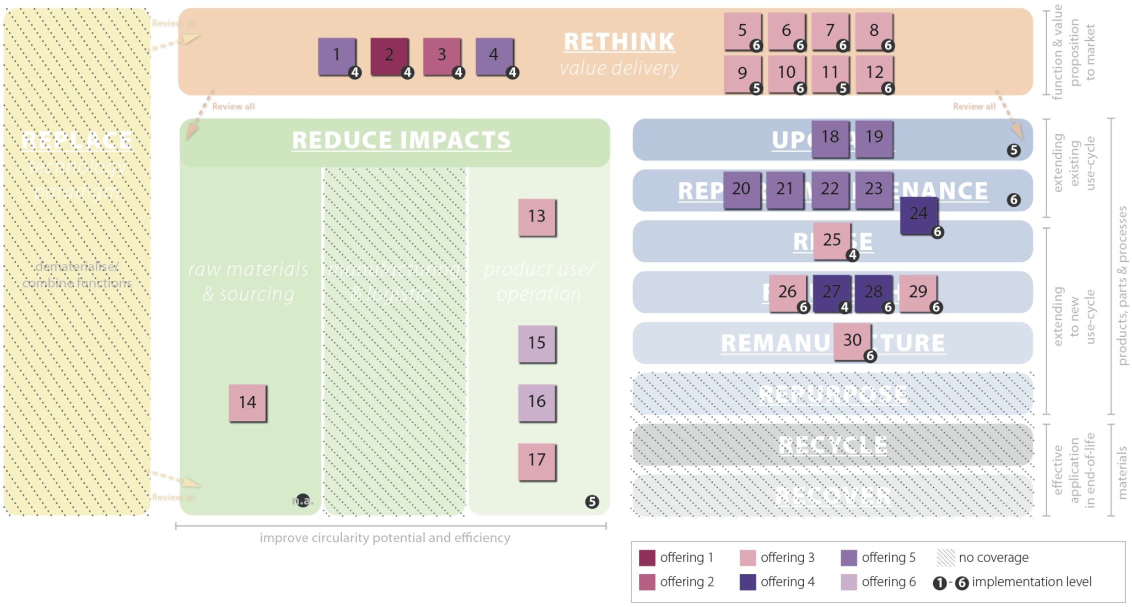
However, observations were made that were used to improve the framework further. First, it was noted that efficient logistics is relevant throughout a product’s life, and not just before, during and after manufacturing. That is: for operations extending existing life cycles or those that extend the product life to new use-cycles and in recovering materials for end-of-life treatment, logistics must be cost- and carbon efficient. It should be placed in such a way to indicate this broader relevance.

Moreover, it was observed that it is also possible to use the sourcing stage as an opportunity to recapture waste that has already entered the environment. The various projects around recovering plastic from the oceans are examples of this (The Ocean Cleanup 2018, Plastic Oceans 2018), and the framework should also highlight the possibility of sourcing such materials. These observations led to the Medium adaptations 1 and 2 discussed in the next section, see also Appendix C.

[4] For more on this, see the CIRCit website (circitnord.com).

Mapping of current and possible company strategies using Circular Strategies Scanner v1.0

Mapping of strategies currently applied on the first version of framework



Opportunity finding - strategies to be added or improved

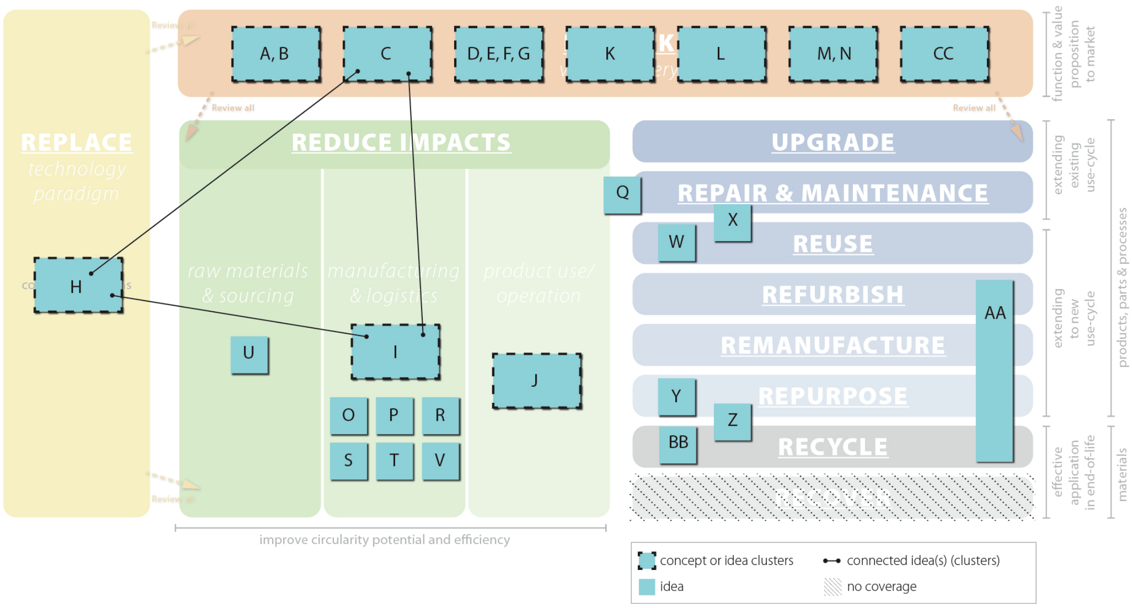


Figure 4 - Example of how the first version of the Circular Strategies Scanner was used in a two-part workshop with one of the companies participating in the CIRCit project. One or double letters are used per strategy: connected or grouped ideas represent closely related ideas that together constitute a new concept. Results are anonymised for reasons of confidentiality.

7. Prescriptive study II

The aim of this phase was to develop a second version of the framework on the basis of the identified improvement opportunities. The main activities were ongoing development efforts, supplemented by a series of meetings held to discuss the implementation of the suggested changes stemming from *Descriptive Study II* and the continued iteration of the *Research Clarification* and *Descriptive Study I.*

7.1. Outcomes Prescriptive Study II

No major adaptations were made, therefore the focus here is on medium adaptations: see for the second version of the framework Figure 5 and the complete set of changes Appendix B. See for definitions of individual strategies Table 2.

'Logistics' was assigned a separate layer such that it encompasses all the operational process areas. In addition to this and in a response to additional sources considered, 'Energy' was added as a layer encompassing all circular strategies (Cullen, 2017; Mestre and Cooper, 2017). That is: circular strategies should be considered with the intent to reduce overall energy consumption, and the use of clean(er) and renewable sources wherever possible.

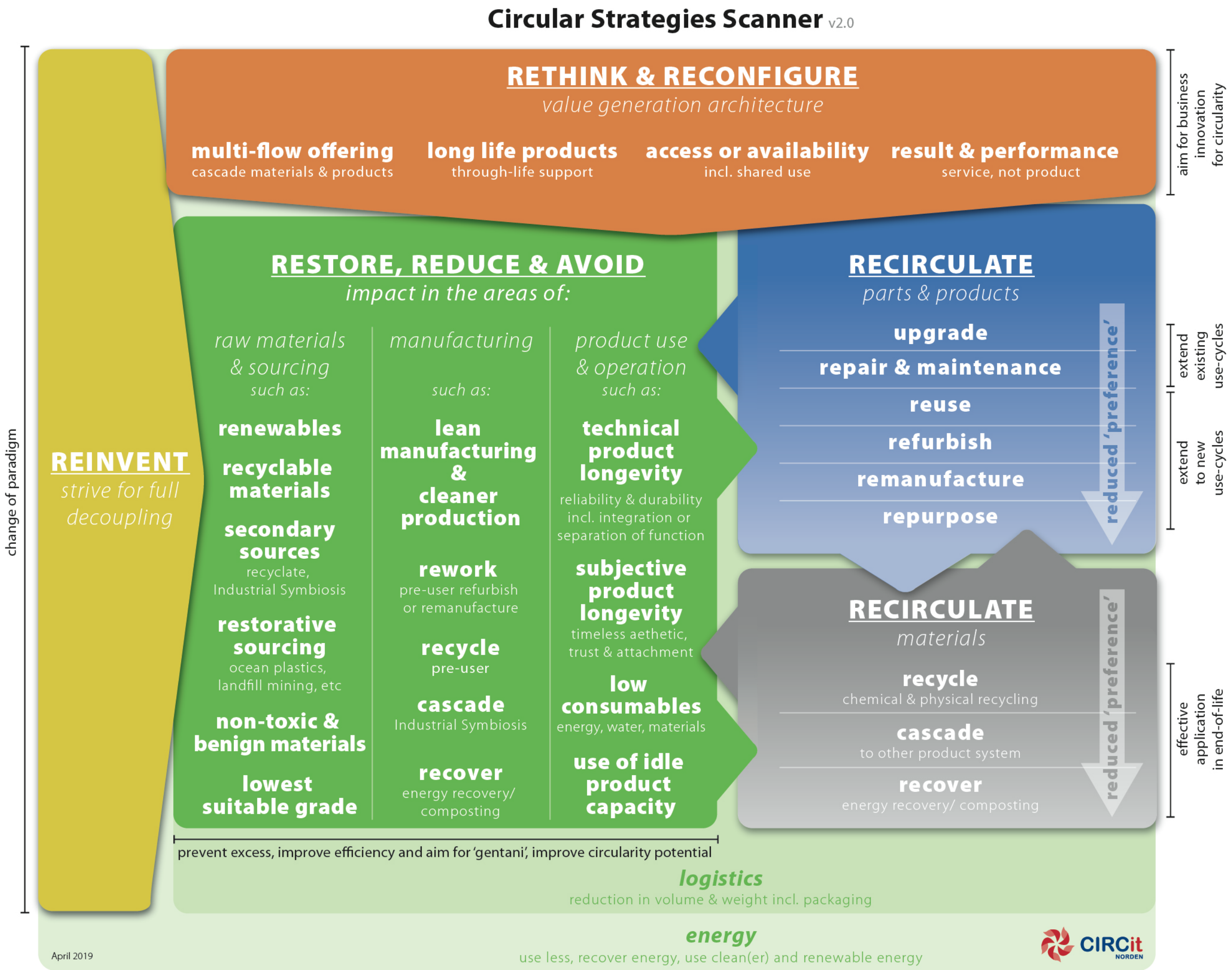


Figure 5 - The second version of the Circular Strategies Scanner.

Moreover, the heading 'Reduce impacts' was changed to 'Restore, reduce & avoid' to more fully reflect the range of strategies relevant for raw materials and sourcing, manufacturing, and product use and operation.

Also, more detail was added to the visual representation of the framework, which entailed the addition of suggested strategies in this area (see Minor adaptation 2). These strategies are meant to be inspirational, rather than exhaustive. In some cases this resulted in allocating strategies to multiple places in the framework, which is in line with Potting et al. (2017) and Reike et al. (2018). Recycling, for instance, can be found in both the category Restore, Reduce and Avoid, as well as in the category Recirculate - Materials. This reflects the fact that pre- and post consumer recycling can take place. Similarly, cascading, or industrial symbiosis can take a variety of different forms: as a sourcing strategy, as a way of valorise manufacturing waste, but also as an end-of-life strategy for materials. These multiple occurrences are also due to departing from the hierarchical structure used by Potting et al. (2017) (see also section *5. Prescriptive Study I*). For clarity descriptors have been added to signal the specific application of a strategy (see Minor adaptation 3).

Similarly, detail was added to the Rethink & Reconfigure category to clarify the framework's relationship with business models aspects. Two sources were consulted for this: Bocken et al. (2016) and Tukker (2004), chosen because of their seminal importance in the CE field (Pieroni et al. 2019) These respective typologies were synthesised into four main categories that cover circular business model strategies available to manufacturers and that represent a fundamental change to the logic of how such a business operates: 'Multi-flow offering,' 'Long-life products,' 'Access or availability,' and 'Result and performance.' This, as opposed to including strategies that are more appropriately thought of as supporting operational strategies such as efficiency and encouraging sufficiency.

Strategies included in the Circular Strategies Scanner (further developed from Potting et al. 2017)		
Driver	**Strategy** Synonyms	**Area of application or sub category** **<u>Recirculation strategy</u>** & synonyms ***Definition*** *(specifics)* ● **Example practice(s)/ specifics**
Enable smarter business concepts through striving for full decoupling.	**Reinvent** Refuse	**The paradigm**
		Make physical products redundant by offering the same function or combined functions, usually enabled by radically different product, technology or both (Potting et al. 2017).
		● The 'bring-your-own' movement facilitates replacing such single use items such as coffee cups. ● Music and video streaming services negate the need for data carriers such as CDs and DVDs. ● Multi-functional devices such as smart phones combine the functionality of multiple devices (camera, GPS, phone, calculator, alarm clock, sound system, computer) in a single device.
Enable smarter business concepts through business model innovation for circularity. Products tend to not radically change, although the technology can evolve.	**Rethink & reconfigure** Revolution Replace	**Business models**
		<u>Multi-flow offering</u> – cascade materials, parts & products
		Extend the life of materials or products in a manner that exploits their residual value and becomes a significant part of the offering of the business. May involve providing new forms of value (Bocken et al., 2016).
		● Leesmap (magazine subscription where the price decreases with the age of the magazines). ● British Sugar (from the core-business of sugar, to also selling many different co-products).
		<u>Long life products</u> – through- life support
		Extend the life of products through offering support during their lifetime (Tukker, 2004).
		● Provision of maintenance, offering of repair services, or sales of spare parts.
		<u>Access or availability</u> – incl. shared use
		Satisfying user needs without transferring ownership of physical products. Instead, user or consumer pays for access to the product for a certain period of time (Tukker, 2004).
		● Bike or car sharing services (e.g. Bycyklen in Copenhagen, Santander Cycles in London, and many other cities around the world; Drive Now, Green Mobility, Zipcar, Blablacar). ● Clothing rental and subscriptions (e.g. Rent the Runway, Vigga, Mud Jeans).
		<u>Result & performance</u> – service, not product
		The provider of the service delivers an outcome for the customer (Tukker, 2004).
		● Performance contracts (Rolls Royce - Power by the Hour).
Prevent excess, improve efficiency and aim for 'gentani', improve circularity potential.	**Restore, reduce & avoid**	**Raw materials & sourcing**
		Improve circularity potential and efficiency in the sourcing process (Mestre and Cooper, 2017).
		● Sourcing of renewables. ● Sourcing of recyclable materials. ● Secondary sources (recycled materials, Industrial Symbiosis, other cascades). ● Restorative sourcing (Use former 'wastes' as input: Landfill re-mining or using ocean plastics). ● Use of non-toxic or benign materials (to facilitate re-absorption in natural cycles). ● Use the lowest suitable grade of materials suitable (Reserve the highest-quality resources for the most demanding task, and use used resources further down the chain).
		Manufacturing
		Improve circularity potential and process efficiency in product manufacture through consuming fewer natural resources or energy, aim for 'gentani' (the absolute minimum input required to run a process) (Potting et al., 2017).
		● Lean manufacturing & cleaner production (use less energy and materials, treat wastes, etc). ● Rework (pre-user refurbishment or remanufacture). ● Recycle (pre-user recycling). ● Cascade (find uses for manufacturing waste: internally/ at other facilities (Industrial Symbiosis)). ● Recover (energy recovery, or recovery of biological nutrients).
		Product use & operation
		Improve circularity potential and efficiency in product use and operation through wiser use and operation of products (usually enabled by digital technologies), and aim for 'gentani' (the absolute minimum input required to run a process) (Potting et al., 2017; Reike et al., 2018).
		● Enable product longevity through high product integrity and robustness. ● Use idle product capacity (historical usage data can be used for improvements such as better scheduling (of downtime), and (give insight into the possibilities for) pooled or shared use). ● Low consumables of energy, water and materials during product use and operation.
		Logistics
		Improve process efficiency in logistics operations, aim for 'gentani' (minimum input into a process (Greenbiz, 2014)
		● Combine forward & return logistics. ● Incentivize eco-friendly driving and transport. ● Minimize, reuse or recycle (transit) packaging.
		Energy

		Improve energy efficiency and use clean(er) sources of energy (Cullen, 2017; Mestre and Cooper, 2017). • Use less energy • Renewable energy

Strategies included in the Circular Strategies Scanner *(cont).*		
Driver	**Strategy**	**Area of application or sub category** **Recirculation strategy** & synonyms ***Definition*** *(specifics)* • **Example practice(s)/ specifics**
Extend existing use cycles with the purpose of capturing (residual) value or to reduce value loss from continued use of parts and products	**Recirculate**	**Parts & products**
		Upgrade – Update, modernize, renew, retrofit, rebuild, overhaul, revive. *Extend existing use cycle by adding value or enhancing the function of a product in respect to previous versions (Parkinson and Thompson, 2003; Potting et al., 2017).* • Aesthetic upgrades (i.e. changing the coat or sleeve of a product due to a new preference). • Functional upgrades (i.e. software upgrades, hardware upgrades).
		Repair & maintenance – Corrective, condition based, predictive and prescriptive maintenance *Extend existing use cycle by countering wear and tear, and correcting faulty components of a defective product/part to return it to its original functionality. ((Partial) disassembly envisioned, limited warranty may be issued). (Thierry et al, 1995; Stahel, 2006).* • Providing a product with a service, which may involve the lubrication of critical parts, checking fasteners, the tension of chains and cables, the replacement of worn-out parts, etc. • Repair may involve the restoration or replacement of faulty parts and components.
Extend to new use cycles with the purpose of capturing (residual) value or to reduce value loss from continued use of parts and products.		Reuse – As-is reuse, redistribution, product cascading, minimise. *Extend to new use cycle by reusing a part/ product (discarded/ not in use) that is still in good condition and can fulfil its original function in a different use context (new customer/user). (May involve a minimum amount of condition monitoring such as cleaning or repackaging. No warranties are provided and no disassembly is involved.) (Saavedra et al., 2013)* • Selling used goods on platforms such as E-bay, • Return and resale of second hand goods through stores, such as Patagonia and Bergans. • The xStorage Home system (by Nissan and Eaton) gives old lithium-ion batteries from Nissan Leaf a second life inside of homes and businesses as backup and solar storage batteries.
		Refurbish – Recondition, retrofit, refresh, remodel. *Extend to new use cycles by returning a part/ product (discarded/ not in use) to a satisfactory working condition that may be inferior to the original specification. (This may involve: cleaning, repairing, resurfacing, repainting, re-sleeving. Partial disassembly envisioned*. In the case of traditional product sales, a warranty for all major parts may be issued (less than the newly manufactured equivalent)). (Ijomah, 2002, 2009; Saavedra et al., 2013).* • For example: taking in relatively modern, but disused white goods and performing repairs and/ or replacing lost parts and finding new users for the refurbished products (e.g. Norsk Omburk).
		Remanufacture – Rebuild, overhaul, remake. *Extend to new use cycles by returning a product (discarded/ not in use) to at least Original Equipment Manufacturer (OEM) performance specification and quality. (Usually more rigorous and costly than refurbishment and involves total disassembly and reassembly. In the case of traditional product sales, a warranty that is at least equal to that of a newly manufactured equivalent may be issued). (Ijomah, 2002, 2009; Saavedra et al., 2013).* • Renault engine blocks
		Repurpose – Alternate use. *Extend to new use cycles by using a product (discarded/not in use) or its parts for different functions (Potting et al., 2017; Reike et al., 2018).* • Mærsk providing containers to fit housing purposes in Copenhagen Village. • Using product packaging as storage or glassware (Nutella, Douwe Egberts).
Effective application in end-of-life of materials with the purpose of capturing (residual) value or to reduce value loss from continued use of materials.	**Recirculate**	**Materials**
		Recycle *Extend material lifespan by processing them in order to obtain the same or comparable quality (Allwood et al., 2011).* • Can-to-can recycling in beverage cans. • Chemical recycling of nylon.
		Cascade – Downcycling, upcycling. *A subsequent use that significantly transforms the chemical or physical nature of the material (Sirkin and Ten Houten, 1994).* • Repurposing of used clothing as an insulation material. • Used coffee grounds from coffee shops processed into biofuel, as medium for cultivation of edible mushrooms, for use in beauty products, etc.
		Recover *Recover energy or nutrients from composting or processing materials. (Reike et al., 2018).* • Incineration, pyrolysis or anaerobic digestion (recovery of energy). • Composting (recovery of biological nutrients).

Table 2 - Overview of the definitions of the circular strategies as used in the Circular Strategies Scanner.

8. Discussion

The Circular Strategies Scanner illustrates how to support visioning in COI processes, through supporting the explication of CE, mapping current CE initiatives, and generating ideas for increased circularity. With this, the framework of Potting et al. (2017) was significantly improved upon for the manufacturing context, see Table 3.

Criteria **The new framework should:**	**Potting et al. (2017)**	**Circular Strategies Scanner - v2.0**	**Summary of improvements that were realised**
01) A tool for inspiring, motivating and aligning people.	++	+++	*Improved capacity to serve as a boundary object where stakeholders can clearly identify their (influence on) activities, and see the applicability and relevance of circular strategies (see also the criteria below).*
02a) Balance the generation of new ideas, with that of describing existing situation.	++	+++	*The Scanner can directly and without transformations be used as a tool for mapping the circular strategies that are present in a situation, as well as for exploring what strategies can be improved or added (see section 6).*
02b) Provide an overview of the spectrum of available strategies ranging from incremental to transformative.	++	+++	*The Scanner groups circular strategies according to their potential for change in circularity levels. Strategies that can be thought of as having potential for incremental change are grouped under* Restore, reduce & avoid*; strategies that aim for higher levels of circularity through business model innovation are grouped in* Rethink & reconfigure*; and strategies that radically transform both business and user practices and achieve radical decoupling are placed in* Reinvent*.*
03) Indicate which strategies affect which business processes and related capabilities.	+	++	*The circular strategies in the Scanner are organised according to the business processes they apply to.* Reinvent *and* Rethink & reconfigure *represent groups that affect business strategy, and the remaining groups respectively affect operational processes, ranging from raw materials and sourcing, manufacturing, product use and operation, to the recirculation of parts and products, and materials.*
04a) Explicitly include the reduction and avoidance of resource use and impacts, as well as resource productivity strategies aimed at continued use and value delivery.	++	+++	*The Scanner covers a wider range of circular strategies, giving a more comprehensive overview of circular strategies that aim for the reduction and avoidance of resource use and impacts, as well as those that improve resource productivity strategies.*
04b) Allow for generating insight into circular configurations.	++	+++	*The Scanner implements a means of systematically exploring connections between circular strategies, through organising them in three 'levels' that indicate their relationship. This relationship can be bi-directional: e.g. a change in circular strategies in* Restore, reduce & avoid *may impact the circular strategies in* Recirculate and vice-versa*; or it may may be a unidirectional relationship where a change in* Reinvent *requires the reexamination of the relevance of circular strategies in* Rethink & reconfigure, *or where a change in* Rethink & reconfigure *requires a reconsideration of the strategies applied in* Restore, reduce & avoid.
05) Has to point to the value drivers that circular strategies can contribute to.	++	+++	*Each group of circular strategies in the Scanner is clearly linked to a value driver that aids its users in identifying relevant contributions to value creation and capture, such as improved efficiencies, supporting optimal use during the use phase, and value recovery opportunities, pointing to opportunities for either financial or non-financial gains within or outside the company.*
+++ = framework satisfies criterion very strongly, ++ = framework satisfies criterion strongly, + = framework satisfies criterion moderately, 0 = framework doesn't meet criterion or only marginally.			

Table 3 - Overview of the the improvements that the new framework makes in relation to the framework by Potting et al. (2017) that was used as a basis for its development.

A strength of using the Scanner in COI is that it provides a way of systematically exploring circular strategies. It thus provides guidance in identifying what business areas eco-innovation for CE is possible or necessary. For instance, when improved recycling is identified as an opportunity, the Scanner indicates that other circular strategies in the operational areas of raw materials and sourcing, manufacturing, product use and operation, and the recirculation of parts and products may be affected. Such impacts may be synergistic and result in increased overall circularity (e.g. the choice to change to a recyclable material to enable end-of-life recycling also enables recycling of waste within the manufacturing process), or they may take the form of trade-offs and require additional management or development for resolving them (e.g. changing to a recyclable material negatively affects the technical longevity of a product). Further work could focus on providing additional guidance with regards to how to systematically identify synergies and trade-offs.

Application of the Scanner furthermore strengthens the connection between eco-innovation and CE, by linking it with transformative innovation (De Jesus et al. 2018). It does this in two ways in COI processes. First, due to possibilities uncovered in the operational area, it can trigger a re-evaluation of the value generation architecture. Second, when the value generation architecture is the starting point, the Scanner indicates that the role of the circular strategies on the operational level need to be revisited as their relevance may increase or diminish depending on the context. In both cases, the Scanner invites a reconsideration of the system the manufacturing company is attempting to transform and links circular strategies together in circular configurations: situations where two or more circular strategies work together (Blomsma et al., 2018).

The range of sectors used for the validation efforts - heavy machinery, electronics and furniture - points to the broad applicability of the Scanner for manufacturing companies from different sectors. However, the framework could be further strengthened by validation with a wider set of manufacturing companies, including those that (also) operate within the biocycle, or that provide dissipative products (e.g. paints, lubricants, cleaning agents and other chemicals).

Further work should address how the Scanner can be linked to the assessment of (combinations of) circular strategies and different implementation scenarios, such that in the early stages of innovation processes the impact on economic, environmental and social systems can be evaluated and actions implemented to minimise negative impact and maximise positive impact. It could furthermore be explored whether the framework has potential to address the lack of a common understanding between value chain actors, which is perceived as an obstacle for the implementation of CE (Machacek et al. 2017; Lapko et al. 2018). In addition to using the Scanner by itself, there is also a need for understanding how different classes of circular strategies frameworks (e.g. macro, meso, micro, nano, networked) can best be used together.

9. Summary and conclusion

With this paper, we have contributed to the development of support tools for CE oriented innovation, or COI and to enable the translation of the CE concept in practice by creating support for visioning for CE. The contribution of this paper is four-fold: a) it provides an example of a process of how a circular strategies framework can be developed for a specific business type with the ability to support COI processes, b) it proposes a circular strategies framework for the manufacturing context, with c) an accompanying set of definitions of circular strategies, and d) it provides an example of how such a framework can be used in the early stages of a COI process. Next, it will be discussed how each goal was achieved and what the implications are for academia and industry.

In support of the first goal - to provide an example of the development of a circular strategies framework - this paper used the lens of Design Research Methodology (Blessing and Chakrabarti, 2009). This answered the call for the more deliberate and systematic development of circular strategies frameworks that are fit for purpose, voiced in Niero and Hauschild (2017) and Blomsma (2018). With manufacturing companies as the focus, it provided an example of how academia and industry can work together following a transdisciplinary approach (Sakao and Brambila, 2018) in developing resonant frameworks for specific audiences. The systematic development approach followed in this paper can be adapted and further expanded upon for other business types or other innovation contexts.

The second goal was achieved through the provision of the Circular Strategies Scanner. This framework can be used as a tool in COI and provides practitioners in manufacturing with a way of contextualising the CE concept, mapping current CE initiatives, and generating ideas for increased circularity. The third contribution, the set of circular strategies definitions included in the framework, served to support the consolidation of CE terminology and bringing academic and practitioner terminology closer together (Reike et al. 2018; Meste and

Cooper 2017; Kalmykova et al., 2018). This was achieved through drawing on both academic and practitioner perspectives with regards to these definitions in the development process. Together, these two points mean that an important iteration on the framework provided by Potting and colleagues was made, which brings more precision to the framework and which customises it for the manufacturing context. With this, the framework has been transformed from analytical framework into an innovation tool.

The fourth goal was achieved through illustrating how the Circular Strategies Scanner can be used in the early stages of a COI process to create a shared vision. The examples provided are of its application within businesses (see section 6). As well as with these companies, the Scanner was used with the other manufacturing companies participating in the CIRCit project. Specifically, it was used in the early stages of the action research, which allowed for a clear vision to be developed and establishing a clear direction for the work that followed, as it clarified with what aim different business activities relevant for COI needed to be deployed, whether this involved sustainability assessment, business model innovation, product design, digital technology strategies, the creation of take-back systems or value chain design.

Equally the Scanner could be applied across businesses, but also between business and academia, and beyond. In these contexts, the Scanner can serve as a boundary object where the stakeholders can clearly identify their activities or influence on different business processes across the life cycle, also enabling the comparison of CE initiatives and sharing of best practices.

Acknowledgements
This article is one of the outcomes of the research project CIRCit (Circular Economy Integration in the Nordic Industry for Enhanced Sustainability and Competitiveness), which is part of the Nordic Green Growth Research and Innovation Programme (grant numbers: 83144) and funded by NordForsk, Nordic Energy Research, and Nordic Innovation. We would also like to thank the companies participating in the CIRCit project and the anonymous reviewers whose thoughtful feedback aided the development of this work.

Appendix A

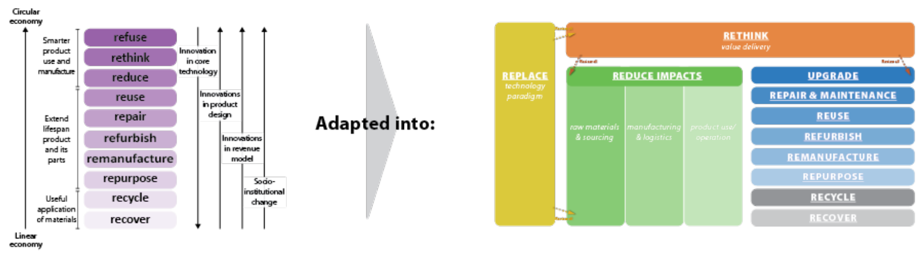
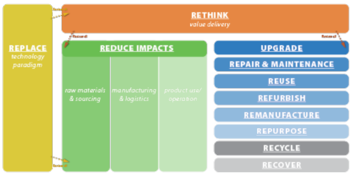
Overview of changes to adapt the Potting et al (2017) framework for the manufacturing context		
		
Major adaptations - changes in the structure of the framework		
#	In Potting et al (2017):	First version of Circular Strategies Scanner:
1	Circular strategies organised hierarchically: ranging from those that are considered more linear to those that are increasingly more circular.	Circular strategies are organised according to the business functions they apply to, in five main areas: *Replace*, *Rethink*, *Reduce Impacts* and two other operational process areas respectively containing end-of-use and end-of-life strategies
2	'Reduce' presented a single high-level strategy.	Specified into 'Reduce impacts' and the sub-categories of 'raw materials & sourcing,' 'manufacturing & logistics,' and 'product use/ operation.'
3	-	A visual structure consisting of three levels has been created to indicate the relationship of circular strategies, through the relative placement of the boxes containing the strategies, and the addition of arrows.
Medium adaptations - changes to the sub-groups or categories of the framework		
1	Inclusion of *Refuse* at the top of the hierarchy.	In the Circular Strategies Scanner, this strategy is understood as consisting of two sub-strategies and it was therefore split in two: *Refuse* (to abandon a practice altogether) and *Replace* (see Table 2). *Refuse* was subsequently not included in the framework, due to this framework targeting companies (see also Discussion section).
2	Contains the value driver: "Smarter product use and manufacture" for *Refuse*, *Rethink* and *Reduce*.	To refine this further, this value driver was split into "dematerialise/ combine functions" for *Replace*, "function & value proposition to market" for *Rethink*, and "improve circularity potential and efficiency" for *Reduce Impacts*.
3	Contains the value driver: "Extend lifespan of products and parts" for *Reuse*, *Repair*, *Refurbish*, *Remanufacture* and *Repurpose*.	To refine this further, this value driver was split in two to align with the end-of-use and end-of-life groupings as in line with Potting. As a result, *Upgrade*, *Repair & Maintenance* and *Reuse* are assigned the driver "Extending existing use-cycle," and *Refurbish*, *Remanufacture* and *Repurpose* are assigned the driver "Extending to new use-cycle."
Minor adaptations -- refinements in labels, definitions and the order of circular strategies		
1	Inclusion of *Recover*, as a strategy that refers to energy recovery through incineration, anaerobic digestion, pyrolysis.	The definition of *Recover* has been expanded to also include the recovery of biological nutrients and as such also covers such strategies as composting.
2	-	*Upgrade* was added to the framework to make explicit evolving quality and performance requirements of products.
3	*Reuse* comes before *Repair* in strategy order.	The order of *Reuse* and *Repair* was reversed, as Reuse that involves mere redistribution of products will – theoretically – maintain value to a higher degree with less added investment of resources, than redistribution that is also combined with repair activities.
4	Includes *Repair* as a circular strategy.	Repair was extended to also include maintenance, which is a common terminology in companies, and as such is indicated as *Repair & Maintenance* in the framework.

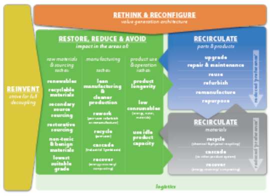
Table - This overview explains which changes were made to the Potting et al (2017) framework in order to adapt it to the manufacturing context. It gives a complete overview of the major, medium and minor adaptations.

Appendix B

Overview of changes to refine the 1st version of Circular Strategies Scanner and develop the 2nd version



Further refined into:



Medium adaptations - changes to the sub-groups or categories of the framework

#	First version of framework	Second version of Circular Strategies Scanner:
1	The process of *Logistics* featured alongside *Manufacturing*.	*Logistics* is assigned a separate area in the framework, to better reflect that it covers all the operational process areas.
2	-	*Energy* was added as a relevant layer. That is: circular strategies should be considered with the intent to reduce overall energy consumption, and use clean(er) and renewable sources wherever possible.
3	Featured the strategy *Reduce Impacts*.	Label of strategy was changed to *Restore, Reduce and Avoid* to more fully reflect the range of strategies relevant for raw materials and sourcing, manufacturing and product use and operation.
4		Explicit addition of relevant strategies in *Restore, Reduce & Avoid.* Such as restorative sourcing (i.e. re-mining from landfill or using ocean plastics), lean and cleaner production practices and using idle product capacity. *Cascade* was also included: it can occur as Industrial Symbiosis and either as a secondary source sourcing strategy, or as a way of managing the co- and byproducts from manufacturing.
5	No detail provided regarding Rethink & Reconfigure.	To clarify the framework's relationship business models aspects, detail was added to the Rethink & Reconfigure category. This was done by drawing on Bocken et al. (2016) and Tukker's (2004) and adding the four main categories of Multi-flow offering, Long-life products, Access or availability, and Result and performance.
6	No explicit place for product and process design.	Product and process design are explicitly acknowledged by including them as box between Rethink & Reconfigure and the operational process of Restore, Reduce & Avoid and the Recirculate parts, products & materials.

Minor adaptations - refinements in labels, definitions and the order of circular strategies

1	Value drivers largely based on Potting et al. (2019).	Value drivers were further refined: for *Reinvent* it was changed to "strive for radical decoupling," and for *Rethink* to "aim for business innovation for circularity," and for *Restore, Reduce and Avoid,* to "prevent excess, improve efficiency and aim for 'gentani' and improve circularity potential."
2	Visual structure consisting of three levels has been created to indicate the relationship of circular strategies, through the relative placement of the boxes, and the addition of arrows.	Visual layering emphasised through depicting it using the visual metaphor of physical layers, which takes the form of drop shadows and arrows to indicate the relationship between the process areas. Hierarchical relationships indicated by a single arrow, trade-offs and synergies by bi-directional arrows.
3	No indication of hierarchy of end-of-use and end-of-life strategies	Arrows were added to indicate the (theoretically) preferred application order of these strategies.
4	Headings only applied for *Replace, Rethink* and *Reduce Impacts.*	For consistency, all five process areas are given headings. End-of-use processes are titled *Recirculate – parts & products* and end-of-life processes are titled *Recirculate – materials*.
5	-	*Cascade* was added to *Recirculate – materials*. This adds the distinction between recycling – i.e. those processes that keep material circulating at or near virgin levels of performance, and cascades – i.e. those processes that extend the life of materials through allowing for reduction or redefinition of performance characteristics.
6		Addition of descriptors to strategies to aid in clarifying the type of application. For example: recycling can take place at the manufacturing stage, where it involves re-entering waste from the manufacturing process back into the process: pre-user recycling. It can also take place post-user at the *Recirculate – materials* stage, in the form of chemical or physical (mechanical) recycling.
7	Featured the strategy label *Replace*.	*Replace* was changed to *Reinvent - strive for full decoupling*, to prevent confusion in relation the replacing harmful chemicals with less harmful or benign ones. Moreover, this term better conveys the transformative nature of this strategy.
8	Featured the strategy label *Rethink value delivery.*	Changed to *Rethink & Reconfigure value generation architecture.*

Table - This overview explains which changes were made to the first version of the framework in order to develop the second and final version. It gives a complete overview of the medium and minor adaptations. No major adaptations were made at this stage.

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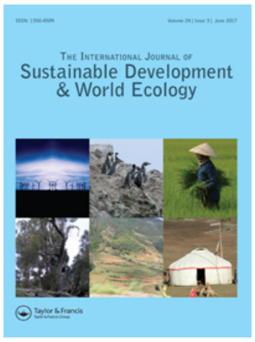

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International Journal of Sustainable Development & World Ecology

ISSN: 1350-4509 (Print) 1745-2627 (Online) Journal homepage: https://www.tandfonline.com/loi/tsdw20

Sustainability assessment tools – their comprehensiveness and utilisation in company-level sustainability assessments in Finland

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INTERNATIONAL JOURNAL OF SUSTAINABLE DEVELOPMENT & WORLD ECOLOGY, 2017
VOL. 24, NO. 3, 236–247
http://dx.doi.org/10.1080/13504509.2016.1204636

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ABSTRACT

Companies have a central role in the transition towards more sustainable economic systems, as they are one of the major sources of environmental impacts, economic activity and social development. Various tools are available to support sustainability assessments, but there is little information on how suitable they are for company-level assessments and how companies use them in real-life applications. The article examines some of the commonly used tools and the utilisation of these tools in Finnish companies. A sample of seven tools was compiled: multi-criteria decision analysis (MCDA), material flow analysis, life cycle assessment (LCA), input–output models, sustainability indicators and indices, cost–benefit analysis (CBA) and optimisation methods. MCDA, LCA, CBA and optimisation methods were found to be successful with respect to many of the criteria used in the evaluation, but none of them was comprehensive. The assessment indicates that MCDA has the greatest potential to be successfully applied to support sustainability assessment, but solely applying MCDA is not suggested, since MCDA needs input from other tools and methods, in order to have reliable impact assessments. Finnish companies regularly employ sustainability criteria and indices, and a few construction companies had applied LCA, but utilisation of other tools was rare. The findings indicate that the tools frequently discussed in research are not actually used by companies. Expert-driven sustainability trials and user-friendly, simplified tools could be a solution to issues of accessibility in real-world applications.

ARTICLE HISTORY
Received 6 June 2016
Accepted 15 June 2016

KEYWORDS
Companies; comprehensiveness; sustainability assessment tools; sustainability reporting; decision analysis

1. Introduction

Many of our planet's limits have been exceeded through actions such as growing use of material resources, which harm the environment and human health (Rockström et al. 2009; SOER 2015; Steffen et al. 2015). This has raised concerns about the sustainability of current economic systems. The discussion of sustainability has its origins in the Brundtland Commission's definition of sustainable development as 'development that meets the needs of the present without compromising the ability of future generations to meet their own needs' (World Commission on Environment and Development 1987). The UN conference on the environment and development held in Rio de Janeiro in 1992 formally adopted the concept of sustainable development, and the term has been used in scientific and political discussions ever since. Furthermore, the number of research articles focusing on sustainable development from a methodological and a conceptual perspective has been increasing in recent decades (Bond et al. 2012; Singh et al. 2012).

Work on the theme of sustainable development is characterised by the presence of extensive multidisciplinary definitions, which are occasionally contradictory (Bolis et al. 2014). Some definitions focus on environmental issues, while broader definitions encompass ethical and social values as well (Bolis et al. 2014). Here we consider sustainable development as a broad concept covering environmental, economic and social pillars. In a company context, this means, for example, that a company should create prosperity and generate work possibilities at the same time (Global Reporting Initiative 2013). Companies have a central role in the transition towards more sustainable economic systems, as they are one of the major sources of environmental impacts, economic activity and social development. Furthermore, companies are among the main consumers of natural resources. Developing eco-friendly designs and sustainability-oriented innovations can bring a company new business opportunities (Klewitz & Hansen 2014). On the other hand, sustainable development can cause challenges for the economic success of a company. For instance, the sustainability of biofuel companies has been questioned greatly because of unexpected negative environmental impacts and also the harm caused to food security (Liew et al. 2014).

Companies invest considerable time and resources in informing their stakeholders about their impacts on sustainability, by, for instance, releasing sustainability

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reports or reporting their sustainability impacts via the Internet (Häkkinen et al. 2013). Sustainability reports may play a key role in how seriously a company takes sustainability into account (Silvestre et al. 2015). These reports describe the company's impact on sustainable development (e.g. emissions related to climate change and employment figures) (Global Reporting Initiative 2013). Reporting is a way of communicating with stakeholders, but there is little correlation between the performance of environmental disclosure in reports and economic variables (da Rosa et al. 2013). Another issue is that information on how sustainable strategies are developed in practice is not available (Egels-Zandén & Rosén 2015).

To increase their role in supporting sustainable development, companies need to detect the sources of their main impacts and assess how their operations influence sustainable development. To bring structure to sustainable development assessments, various tools can be utilised (e.g. Singh et al. 2012; Myllyviita et al. 2014). Sustainable development has been one of the most highly recognised topics in the field of research devoted to methodological development and operational research (e.g. Mustajoki et al. 2011; Myllyviita et al. 2013). There are several structured methods and less formal tools available, and the number is likely to increase (Gasparatos 2010; Poveda & Lipsett 2011). Consequently, definition and classification of tools is a complex matter. These tools serve as an 'attempt to understand a system and offer information in a format that can assist the decision making process' (Gasparatos et al. 2008).

Several reviews of sustainability assessment tools are available in the literature, but the scope and the purposes of these reviews are highly varied. Hörisch et al. (2015) tested the impact of implementing sustainability management tools on key dimensions of corporate environmental performance. Their analyses indicate that different tools are effective for different purposes. One limitation of their research is its focus solely on large companies. Ferreira et al. (2013) reviewed decision support tools used in the building refurbishment sector and concluded that, as the decision-making process is usually time-consuming, it is important to make the process faster and more effective. Hence, a successful tool should be fairly simple and straightforward to use. Additionally, Sharifi and Murayama (2013) revealed that the sustainability assessment tools embedded within the broader planning framework are successful with regard to applicability. Myllyviita et al. (2011) reviewed decision support tools used to encourage sustainable use of forest resources. In their review, the case studies utilising hybrid approaches (i.e. simultaneous use of qualitative and quantitative tools) showed more active participation of stakeholders than those case studies in which only a single tool was applied. Lozano (2012) provided an analysis of 16 of the most widely used sustainability assessment tools and determined that 'each initiative has advantages with respect to scope and focus for the sustainability dimensions and the company system's elements, but it has certain disadvantages when it comes to dealing with the complexity and broadness of sustainability'.

Even though there has been active methodological and conceptual discussion of sustainable development, fewer studies have been done on the utilisation of tools at the company level (e.g. da Rosa et al. 2013; Egels-Zandén & Rosén 2015). In some cases, the results of the sustainability assessments have led to major changes in the ways the company operates. For instance, the carbon footprint of cola cans and bottles has been assessed since the 1960s, and the findings have greatly influenced how a company packs its products. One major problem is that small and medium-sized enterprises (SMEs) lack the resources, time and methodological expertise required (Crals & Vereeck 2005; Häkkinen et al. 2013; Judl et al. 2015), although some SMEs have done extensive work connected to sustainability-orientated innovations (Klewitz & Hansen 2014). As SMEs represent more than 80% of companies operating in Europe, they have been identified as significant contributors to sustainable development (Biondi et al. 2002). The best available knowledge and lessons learned should be presented in an understandable format for company uses to advance companies' role in implementing sustainable development in practice.

SMEs have an important role in Finland: they are a source of national competitiveness (Akola & Havupalo 2013). Altogether 98% of Finnish enterprises were classified as SMEs in 2009 (Akola & Havupalo 2013). Finland and Finnish enterprises use a significant amount of natural resources, and the national carbon footprint has remained high despite efforts aimed at resource-efficiency (Putkuri et al. 2013). On a governmental level, Finland is committed to promoting sustainable economic growth and the sustainable use of its natural resources; this is seen in, for example, the Government programme and the Government strategy to promote the cleantech business (Finnish Government 2014; Ministry of Employment and the Economy 2014). Finland has agreed on several sustainable development targets. These targets include reduction of greenhouse gas emissions of at least 80% by 2050 from 1990 levels (Ministry of the Environment 2014) and recycling or materially recovering 70% of non-hazardous construction and demolition waste by 2020 (European union 2016). Therefore, it is interesting to see how companies in a seemingly committed country such as Finland measure and assess their sustainability in practice.

There is an enormous amount of research focusing on sustainability assessment tools, but only a few of the studies have addressed actual utilisation of these tools at the company level. This is an important topic, as companies are major players in the transition towards sustainable economic systems. Our overall target was to compare the utilisation of sustainability assessment tools between research articles and the company level. The first aim was to assess the success of seven sustainability assessment tools. This sample of seven tools was compiled on the basis of a review of research articles. The specified success criteria (previously defined by Myllyviita et al. (2014) were used in the assessment of these tools. Our second aim was to gain insight into the utilisation of these tools in company-level sustainability assessments. To do this, we carefully reviewed sustainability reports and web pages of 127 Finnish companies. Companies from four sectors (energy, hotels and restaurants, mining and construction) were included. From this analysis, we describe the success of the seven sustainability assessment tools and discuss their benefits and limitations. Furthermore, we illustrate the current state of the utilisation of these tools at the company level sustainability assessments. Finally, proceeding from our extensive surveys, we describe means to advance the utilisation of these tools and ways to support sustainability assessments of companies.

2. Material and methods

There are three parts to the body of this paper: (1) an evaluation of the sustainability assessment tools commonly used in research articles; (2) a review of the utilisation of these tools in Finnish companies; and (3) a comparative assessment in which we evaluate whether Finnish companies apply these tools (see Figure 1).

2.1. Tools to assess sustainability – a review

A sample of tools used to assess the sustainability of companies in research articles was selected using Web of Knowledge database. The search keys were: sustainability, economic and systems. These search keys were considered to point to a wide range of studies wherein various sustainability assessment tools were used. On the basis of the search, a sample consisting of 50 articles' abstracts was studied, and the tools used in the articles to study sustainability were included in our assessments. As a result of the article review, a sample of seven tools was obtained, which are as follows: multi-criteria decision analysis (MCDA), material flow analysis (MFA), life cycle assessments (including environmental, economic, social and sustainability aspects) (LCAs), input–output (IO) models, sustainability indicators and indices, cost–benefit analysis (CBA) and optimisation methods.

2.1.1. Multi-criteria decision analysis

MCDA is a group of diverse methods that help decision-makers to identify and select preferred alternatives, when faced with a complex decision problem characterised by multiple objectives (Belton & Stewart 2002). MCDA is, typically, based on preference measurement: that is, the decision-maker is able to state whether they prefer an option A or B and also determine the strength of his/her preferences. In a discrete choice set up, there is a limited amount of alternatives to be considered, whereas in a continuous set up the number of alternatives can be infinite. MCDA is a commonly used method in sustainability assessments, because of its ability to deal with conflicting and incommensurable aspects such as environmental, economic and social dimensions (Merad et al. 2013; Myllyviita et al. 2013).

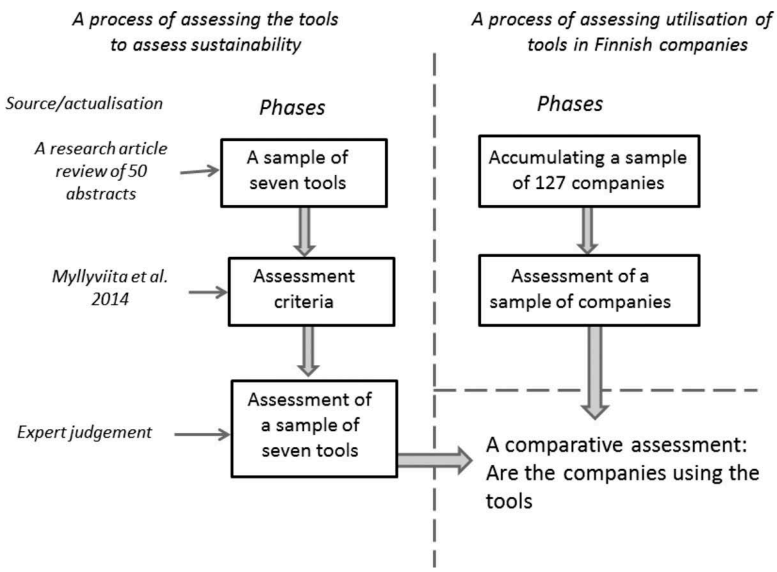

Figure 1. A flowchart for evaluation used in this paper. The process included a systematic evaluation of sustainability assessment tools commonly used for academic research purposes. We also reviewed the web pages and sustainability reports of Finnish companies to assess how these tools are used in practice.

2.1.2. Material flow analysis

MFA (and a subtype of it, substance flow analysis) refers to the analysis of the throughput of process chains comprising extraction or harvest, chemical transformation, manufacturing, consumption, recycling, and disposal of materials (Bringezu & Moriguchi 2002). The MFA process is based on physical units quantifying the inputs and outputs of materials or substances related to those processes. The system analysed may be geographical (e.g. a nation) or functional (e.g. a sector). The principle underlying the economy-wide MFA approach involves a simple model of the interrelation between the economy and the environment, in which the economy is an embedded subsystem of the environment and dependent on a constant throughput of materials and energy (Hinterberger et al. 2003).

2.1.3. Life cycle assessment and other life cycle methods

LCA is a method assessing the environmental impacts of a product or a service from the cradle to the grave. Guidelines for conducting an environmental LCA are given in the standard by International Organisation for Standardisation (ISO) 14040:2006 (ISO 2006). While LCA has some similarities with MFA, the latter is based on assessing a single material or substance, whereas LCA considers several impacts and materials. Various impacts, such as climate change, acidification and toxic emissions, can be included in the LCA. Life cycle costing (LCC) is an approach that assesses the total cost of an asset over its life cycle, including initial capital costs, maintenance costs, operating costs and the asset's residual value at the end of its life (Sesana & Salvalai 2013). Social LCA (SLCA) is developed towards evaluating social impacts, such as employment, workplace health and equity (Benoît 2009; Macombe et al. 2013). This approach is based on the same principles as LCA, but the methods are not well-established yet. So far, SLCA has only been applied for a limited number of cases, but the topic is greatly discussed in the field of LCA (Benoît 2009; Jeswani et al. 2010; Macombe et al. 2013). Life cycle sustainability assessment (LCSA) integrates environmental, economic and social aspects simultaneously, but so far, this topic has remained at a conceptual level (Hoogmartens et al. 2014).

2.1.4. Input–output models

The IO model is a quantitative method that describes the interdependencies between different branches of the economy. The model is based on analyses originally developed by Leontief (1936). The environmentally extended IO (EEIO) analysis is a method for evaluating the linkages between economic consumption activities and environmental impacts. This is an extensively utilised method for assessing the consumption-based drivers of environmental impacts (e.g. Koskela et al. 2011; Kitzes 2013).

2.1.5. Sustainability indicators and indices

The efforts to develop sustainability indicators and indices have increased since the beginning of the 1990s (Rinne et al. 2013). Some of the most commonly used sustainability indicators are connected to gross domestic product and greenhouse gas emissions, for example. The aim behind the indicators and indices is to simplify, quantify, analyse and communicate complicated information to support policymaking and public communication (Singh et al. 2012). Much conceptual and empirical research exists on criteria for sustainability and development of sustainability indicators, while fewer studies focus on the utilisation of sustainability indicators (Rinne et al. 2013).

2.1.6. Cost–benefit analysis

CBA is a method that estimates the equivalent monetary value of the benefits and costs of a project. Based on CBA, it is possible to state whether the project is worth pursuing. The basis of CBA is on economic metrics. However, the concept of sustainable development can be included into CBA. This would, however, require some changes in CBA, such as including, for example, the Social Discount Rate (Sáez & Requena 2007) and monetary valuation of the ecosystem services (Pearce et al. 2006). While also including non-priced external effects in money terms into a standard CBA, this can be referred to as an 'extended' CBA (Brouwer & van Ek 2004). These improvements notwithstanding, valuation of ecosystem services has been highly criticised (see, e.g., Kumar & Kumar 2008 for details), since assigning a monetary value to nature and natural resources has been deemed questionable.

2.1.7. Optimisation methods

Optimisation methods are used to seek an optimal alternative among a potentially infinite number of alternatives. Optimisation methods are a versatile group of methods, ranging from the simplest linear programming to more complex multi-objective optimisation methods. Optimisation methods have been applied in several fields, such as forestry (Diaz-Balteiro & Romero 2008) and the building sector (Evins 2013). Despite the fact that optimisation methods have, typically, been expert-driven tools, integrating stakeholders has been considered to be a necessary part of a process (Maness & Farrell 2004).

2.2. The assessment criteria for the tools

The tools commonly used in research articles to assess sustainability were evaluated. We utilised specific

Table 1. Criteria for assessing tools previously developed by Myllyviita et al. (2014).

Dimension 1: Transparency
-it is clear what is the decision problem and criteria -negative aspects mentioned -justification or reasoning of other decision-makers is presented -analyses and results are clearly stated (from the viewpoint of possible participants)
Dimension 2: Flexibility
-participants can change decision criteria and alternatives -iteration between the phases -new ideas included
Dimension 3: Consensus building
-multiple participants -awareness and acceptance of worldviews -participants engaged from an early stage -conflicts acknowledged
Dimension 4. Operability
-decision criteria are measurable -decision alternatives are compared -trade-offs between decision criteria acknowledged -implementation orientation (yields action plan) -uncertainties analysed

assessment criteria, since it is important to have a unified evaluation framework that treats all tools equally (see Table 1). As there are no widely accepted criteria for this type of assessment, we applied previously developed criteria based on democracy and planning theories, along with participatory planning work by Myllyviita et al. (2014). The criteria were originally developed for use in the natural resources planning process. Our purpose of using these assessment criteria in our study was the detection of a transparent and flexible decision support tool. True underlying decision problems are a precondition also for successful sustainability assessments. In addition, characteristics such as operability are called for. More detailed descriptions of the dimensions and assessment criteria can be found in Myllyviita et al. (2014).

The assessment criteria are grouped under the following four dimensions: transparency, flexibility, consensus-building and operability (see Table 1). Each dimension includes three to five criteria. The definitions of the original criteria were modified slightly, since the criteria were originally developed to assess case studies, whereas the aim for this paper is to evaluate tools.

Dimension 1: Transparency was assessed with four criteria, which aimed to address, if possible, whether participants involved in a process are able to understand the purpose and reasoning behind a tool. Also, a tool should be able to inform about possible negative impacts associated with the decision problem. In addition, a tool should also present the justifications of other decision-makers.

Dimension 2: Flexibility was assessed with three criteria, which aim to assess if a tool has the possibilities to be modified based on participants' wishes. A tool should enable a selection of decision criteria and a modification of the decision alternatives, as well. The possibilities to iterate the process should be a part of a flexible tool.

Dimension 3: Consensus building was assessed using five criteria. With these criteria, the tool's possibilities to address different perceptions related to the decision problem and, thus, increase the probability to reach a consensus are assessed. To reach a mutual understanding, participants should be engaged at an early stage. A successful tool should allow an acknowledgement of possible conflicts and different worldviews.

Dimension 4: Operability was assessed with five criteria that aim to assess whether a tool has possibilities to be efficiently applied to support decision-making. An action plan can be generated if a tool is capable to produce a clear conclusion, that is, define if a certain alternative is better than others. If the generated results are more ambiguous, generating an action plan is more challenging. To increase the operability, the decision criteria should be measurable. Possible trade-offs between them should be acknowledged, since without trade-off consideration some benefits may be maximised at the expense of others. Since uncertainty is, in most cases, significant in sustainable decision-making, a tool should include an uncertainty assessment.

We developed a simple scoring system for the purposes of this paper. Interpretations of the assessment criteria are not absolute (i.e. including new ideas is always attainable, but would require more effort and modifications); therefore, we applied the following scoring system. In the assessment system, '+' indicates that a tool has some possibilities to address the criterion and '++' indicates that this aspect is regularly implemented by the tool. 'O' stands for criterion fulfilment that could not be determined. Finally, '–' implies that a tool has no chance of meeting the criterion. The assessments of all tools were completed by the three authors. The evaluation was completed in a joint meeting, where each tool was assessed with respect to each criterion. In these assessments, we focused on assessing the tools, as they are described in the standards, instruction materials and well-accepted research. First, each author expressed his/her own perceptions and arguments. In the case of a disagreement, a more profound discussion was taking place. Finally, an agreement was reached. Using three expert opinions, instead of one, more reliable results were achieved. Nevertheless, the assessment is influenced by the expertise of the authors; therefore, a different group of evaluators could possibly generate a slightly different kind of results. For instance, iteration is mentioned in the standards for LCA (ISO 2006); therefore, it is safe to say that iteration is a part of LCA. However, the interpretation of some assessment criteria is more subjective. It is not unambiguously possible, for example, to determine whether the 'analyses and results [are] clearly stated'. In this case, some interpretation was required.

2.3. The review of company-level sustainability assessment

Our review of the companies in Finland was accomplished by studying web pages and sustainability reports of the companies. In this review, the aim was to detect utilisation of the seven tools (again, MCDA, LCA, MFA, IO models, sustainability indicators and indices, CBA and optimisation). Altogether 39 energy companies, 20 hotels and restaurants, 20 mines and 48 construction enterprises were included in a review. The companies were selected on the basis of the scale of their total revenue, and the four sectors included were chosen for their importance for sustainable development. Many of the companies reviewed are multinational, and, thus, their performance in Finland also reflects the situation in their other countries of operation. Web-pages and sustainability reports of these companies were carefully studied. First an assistant studied the reports, and did his preliminary analyses. To ensure validity, a senior researcher reviewed the preliminary analyses. If the web pages or sustainability reports of a company showed evidence of the utilisation of a specific tool, a positive observation was recorded (see Table 3, in the 'Results and discussion' section). After reading all the reports and web pages, the percentages of positive observations were calculated. Also, a review on how the companies addressed sustainability (i.e. an assessment on which the dimensions of sustainability were highlighted in their sustainability reports and web pages) was actualised. The percentage of positive observations was also calculated.

3. Results and discussion

Using the Web of Knowledge database for our study, we compiled the sample of seven tools that are commonly used in research articles to support sustainability assessments (see Subsection 2.1 for details). Using predetermined assessment criteria (Myllyviita et al. 2014), we evaluated these tools. Furthermore, we reviewed the sustainability reports and web pages of Finnish companies, as described above, to gain insights into how often these tools are applied in company-level sustainability assessments.

3.1. The assessment of commonly used tools to assess sustainability of economic systems

As a result of the research article review, a sample of seven tools, MCDA, MFA, LCAs, IO models, sustainability indicators and indices, CBA and optimisation methods, was obtained. The seven tools commonly used to assess the sustainability of economic systems in the reviewed journal articles were evaluated with respect to assessment criteria developed by Myllyviita et al. (2014), as explained earlier. Based on three expert judgements, none of these tools was successful with respect to all criteria (Table 2). Nevertheless, MCDA,

Table 2. The results of assessment of the sample of seven commonly used tools to assess sustainability (in the assessment system, '+' indicates that a tool has some potential to address the criterion and '++' denotes this aspect being regularly implemented by a tool, whereas '–' indicates that a tool has no capability to meet the criterion and 'O' stands for criterion fulfilment that could not be determined).

Criteria for assessing tools	MCDA	MFA	LCA	IO-model	Sustainability indicators and indices	CBA	Optimisation
Dimension 1: Transparency							
-it is clear what is the decision problem and criteria	++	–	+	+	–	++	++
-negative aspects mentioned	+	–	++	+*	+	++	+
- justification or reasoning of other decision-makers is presented	+	–	–	–	–	–	–
- analyses and results are clearly stated (from the viewpoint of possible participants)	+	+	+	+	+	++	+
Dimension 2: Flexibility							
-participants can change decision criteria and alternatives	++	–	+	–	–	+	+
-iteration between the phases	++	–	++	–	–	+	+
-new ideas included	++	–	+	–	–	+	+
Dimension 3: Consensus building							
-multiple participants	++	–	+	–	–	+	+
-awareness and acceptance of worldviews	+	–	–	–	–	–	–
-participants engaged from an early stage	+	–	+	–	–	–	–
-conflicts acknowledged	+	–	–	–	–	–	–
Dimension 4. Operability							
-decision criteria are measurable	++	++	++	++	+	++	++
-decision alternatives are compared	++	–	++	+	0	++	++
-trade-offs between decision criteria acknowledged	++	–	+	–	–	+	+
-implementation orientation (yields action plan)	++	+	++	+	+	++	++
-uncertainties analysed	+	+	+	+	–	+	+

* Iif EEIO is applied.

LCAs, CBA and optimisation methods regularly implement many of the assessment criteria. On the other hand, MFA and sustainability indicators and indices were considered to be relatively limited in their capacity to address sustainable development.

MCDA was considered to be a transparent tool (Table 2). When applying MCDA, it is crucial that the decision problem and the criteria are clearly stated, that is, problem structuring is an essential part of the process (Belton & Stewart 2002). Since the target in MCDA is on maximising the utility (or to find the decision alternative with the highest utility or value), the negative aspects associated are often less processed. The justification and reasoning applied by other decision-makers are not presented in MCDA applications (or in any other tool assessed in this paper) unless more in-depth discussions take place (e.g. Mustajoki et al. 2011). Based on weights (which define the importance of decision criteria), participants are able to gain some insights of other participants' preferences (e.g. Belton & Stewart 2002). A typical result of MCDA application is a decision alternative with a highest utility (or in the case of sustainability – the most sustainable); however, it may not be easy for participants to detect how the superior decision alternative has been determined, unless time and resources are allocated for describing the process to the participants (e.g. Mustajoki et al. 2011). Flexibility is one of the benefits of using MCDA, since MCDA allows a modification of the decision criteria and alternatives (e.g. Myllyviita et al. 2013). Iteration and including new ideas into a process are possible, even in a standard MCDA application (Belton & Stewart 2002). Consensus building is moderately well considered in MCDA, since multiple participants are typically engaged (Belton & Stewart 2002). MCDA has some potential to engage participants from an early stage (to structure the decision problem, for example). Conflicts can be acknowledged, since it is possible to incorporate various stakeholder groups into an assessment (Mustajoki et al. 2011). MCDA is successful in terms of operability, since various decision criteria are transformed as measurable and the comparison of decision alternatives is a very basic element of MCDA. An uncertainty assessment in MCDA is not typically actualised in a very sophisticated manner.

MFA appears to be less successful, compared to MCDA (Table 2). This is justified by the fact that the aim of MFA is merely to quantify material flows and stocks in a well-defined system, whereas sustainable development is a far more complex issue. Nevertheless, MFA can transform sustainable development assessment results as comprehensive, comparable and verifiable by (1) providing systematic information and indicators for the assessment; (2) identifying critical pathways, links and key substances; and (3) allowing the dynamic interaction between the material flow and social, economic and environmental processes (Huang et al. 2012). One advanced application of MFA is a connection of MFA with national economics accounts and, thus, enabling the IO models of the economic structures, causing material flows (Koskela et al. 2013).

LCAs appeared to be moderately successful tools to assess the sustainability of economic systems (Table 2). LCA was evaluated to be a moderately transparent method. Nevertheless, the justification and reasoning of other decision-makers are not detectable. Clarity of LCA-generated results and the process itself was not considered to be transparent as the ones generated with MCDA, since LCA is a more engineer-orientated tool and less focus is given to problem structuring (Häkkinen et al. 2013). Nevertheless, goal and scope definition is considered to be a fundamental part of LCA (ISO 2006). LCA is moderately flexible, since iteration is included (ISO 2006). The starting point in LCA is a set of impact categories (e.g. climate change and ecotoxicity), and a relevant set of decision criteria is selected from these. Including new ideas into LCA is not as straightforward as in MCDA, since there may not be suitable characterisation factors (i.e. determinants for the harmfulness of considered emissions) for less established impact categories. LCA has some potential to increase consensus, but tools for conflict management and the acceptance of worldviews are not given within LCA. Operability of LCA is high, since the LCA results are easy to implement: based on a comparative environmental LCA, it is possible to determine the most environmentally friendly alternative. However, it is possible that there are trade-offs between impact categories, that is, the most environmentally friendly alternative cannot be determined without the defining importance of impact categories (Myllyviita et al. 2013). The operability of LCA is moderate, since decision criteria are measurable. Also, uncertainty or sensitivity analysis is customary. However, the sensitivity assessment generally focuses on input parameters, but the uncertainty in LCA may be connected to the system boundaries as well (Mattila et al. 2012).

The IO model was considered to be a less transparent tool than MCDA and LCA, since in IO models, the focus is on the interdependencies between different branches of the economy. Therefore, the IO models are typically utilised at a higher level of decision-making, for example, regional (Liping & Bin 2010), national (Mattila et al. 2013) and global (Wiedmann et al. 2011). IO models can be used in company-level decision-making by generating a hybrid-LCA. In hybrid applications, a standard LCA is compiled, based on data on material and energy consumption, and an economic IO model is used to account for processes for which direct data are not available (e.g. Deng et al. 2011). The flexibility of IO models is lower compared to MCDA and LCA, since decision criteria and alternatives are not easily modified. IO models do not include tools for consensus building, but the operability of the tool is relatively high, because decision criteria are measurable and a comparison of alternatives is attainable. Also, an action plan can be generated, but as discussed earlier, these action plans are typically related to higher-level decision-making. Also, an uncertainty analysis can be conducted, but as in LCA and MCDA, uncertainty assessment is not very advanced in IO modelling.

Unlike the other tools assessed in this paper, sustainability criteria and indices are not methods, but merely tools to structure and communicate information about key issues, and their trends are considered to be relevant for sustainable development (Rametsteiner et al. 2011). Sustainability reports, for example, include a number of sustainability indicators and indices (such as climate-change-related emissions and employment figures) (Global Reporting Initiative 2013). Still, sustainability criteria and indices can bring some new ideas into processes, but they do not have the capabilities to bring consensus as such. Sustainability criteria can also provide some insights into conflicts and different worldviews.

CBA was considered to be a transparent method, since it is understandable, even for laymen. Analyses are clearly stated, as all aspects are expressed in monetary units. However, the decision-makers' justifications are not considered in CBA. CBA is not very flexible, for example, the inclusion of environmental or social aspects of sustainability is not possible as such. However, for instance, ecosystem services can be transformed into monetary units using monetary valuation methods (Pearce et al. 2006). The consensus building of CBA is not advanced, since the focus is only on economics. On the other hand, operability is advanced, since all decision criteria are measurable, and the action plan is generated (i.e. the aim is to reveal whether the plan is reasonable in economic terms). CBA is a potential method for sustainability assessments, as it is simple and comprehensive, but as a sole tool, it is not adequate, since it lacks the means to address other dimensions of sustainability, besides economics. CBA can be adapted to utilise metrics that are different from money, such as employment (Taylor 2001). Therefore, the utilisation of CBA for complex sustainability assessments is attainable (Gasparatos et al. 2008).

Optimisation methods were considered to be transparent, since the decision problem is, typically, clearly stated, that is, there is an aim to define the optimal alternative, including, for instance, some constraints (see, e.g., Evins 2013). Optimisation methods are flexible, since the modification of decision criteria and alternatives is advanced. The consensus building of optimisation methods is moderately low, since tools for engaging participants are not included. The major benefit of using optimisation is operability. This is because of the highly quantitative nature of optimisation methods.

3.2. The tools applied by Finnish companies

The review (Table 3) revealed that the tools available for sustainability assessments are seldom applied by the companies in these four sectors (i.e. energy, hotels and restaurants, mining and construction), at least based on publicly available sources. Sustainability criteria and indices were utilised, moderately, often. However, they are not considered to be methods, but merely tools that can be applied to describe past sustainability trends. In fact, LCA was the only structured method that was applied occasionally (Table 3), but only in the construction sector. In the construction sector, the life cycle perspective is especially important, since the lifespan of buildings can be up to 100 years. Therefore, assessing not only the impacts of the construction phase, but also the whole lifespan of a house (e.g. energy consumption and rebuilding) is important.

Sustainable development was verbally addressed in some manner by most of the companies examined (on their web pages or in their sustainability reports), and these companies gave some information about their role in sustainable development (see Table 4). Different dimensions of sustainability (environmental, social and economic) aspects were, in most cases, addressed. Most of the reviewed companies had compiled a sustainability report (Table 4). Since compiling a sustainability report is a major investment of time and resources, in most cases, only the largest companies will compile a sustainability report. As some of the included energy companies were moderately small, sustainability reports were not often compiled.

Table 3. Percentages of companies applying the various tools to assess sustainability (only sustainability criteria and indices were regularly applied, though companies in the construction sector had applied LCA also) with, in all, 39 energy companies, 20 hotels and restaurants, 20 mines and 48 construction companies were reviewed.

	Sector			
Tool	Construction	Mining	Hotels and restaurants	Energy
Life cycle assessment	17%	0%	0%	0%
Material flow analysis	0%	0%	0%	0%
Input–output models	0%	0%	0%	0%
Multi-criteria decision analysis	0%	0%	0%	0%
Sustainability criteria and indices	63%	50%	60%	69%
Cost–benefit analysis	0%	0%	0%	0%
Optimisation methods	0%	0%	0%	0%

Table 4. The percentage of companies addressing sustainable development and various aspects of sustainability in their sustainability reports or on their web pages (39 energy, 20 hotel and restaurant, 20 mining and 48 construction companies were reviewed).

	Sector			
	Construction	Mining	Hotels and restaurants	Energy
Sustainable development mentioned	60%	65%	60%	90%
Environmental aspects mentioned	63%	70%	65%	87%
Economic aspects mentioned	50%	55%	35%	69%
Social aspects mentioned	63%	70%	65%	80%
Sustainability reports present	63%	55%	50%	10%

In the sectors of construction, mining and hotels and restaurants, sustainability reporting was more common (Table 4).

3.3. Utilisation of tools to support sustainability assessments

The number of publications on sustainability assessment has been increasing over the last decades (Bond et al. 2012). In these publications (see references in Bond et al. 2012), various tools (e.g. LCA, MCDA and CBA) are used to support sustainability assessments. However, we discovered in our study that quite often these tools are not utilised on a company level. It is possible that companies do regularly utilise some of the tools assessed in this paper, but this is not reported. However, if the sustainability assessments are not reported (on company webpages or sustainability reports), the information in these assessments is not usable in decision-making outside companies. Thus, the potential contribution to the transformation to more sustainable companies may remain low. Therefore, it is important that sustainability assessments are reported in a transparent manner.

Based on the results of this paper, it appears that MCDA has the greatest potential to be successfully applied to support sustainability assessments (Table 2). However, it should be acknowledged that, solely, using MCDA to support sustainability assessments is not suggested, since MCDA, in many cases, needs input from other tools and methods, such as LCA (e.g. Elghali et al. 2007), CBA (Brouwer & van Ek 2004) and sustainability indicators (Mendoza & Martins 2006). Furthermore, several other tools seemed promising, but as discussed in the earlier sections, they would require some modifications, such as tools to integrate social aspects and tools to integrate stakeholders, for example. In most cases, the simultaneous use of different methods is beneficial (Myllyviita et al. 2011, 2014). Additionally, there are other tools not included this paper that could be successful, as well (e.g. risk assessment, monetary valuation methods, exergy analysis and several qualitative tools).

A relevant question here is how the tools can be used to assess wider systems than single companies and expand the perspective to the sustainability assessment of economic systems. Deepening the LCA approach by, for example, integrating social and economic dimensions of sustainable development may be beneficial (Jeswani et al. 2010). One option could be to create a toolbox that combines the procedural parts of criteria and indicators and the environmental impact assessment, supplemented with calculation algorithms of LCA and CBA (Buytaert et al. 2011). However, several methodological challenges remain, yet to be solved before these tools can be successfully integrated (Hoogmartens et al. 2014). Special focus should also be given to how these tools are applied, since the facilitator and the way in which the participants are engaged can be more influential than the tool itself (Myllyviita et al. 2014). It is also important to remember that the concept of sustainable development is highly ambiguous and that, in consequence, there are no widely accepted criteria addressing what constitutes a successful sustainability assessment tool. Therefore, the assessments compiled in this paper (especially in Table 2) are not exhaustive either.

3.4. Suggestions for future research: company-oriented sustainability trials

The results presented in this paper (in Table 4, in particular) show that sustainability is in companies' interest, as most of the companies mentioned sustainable development on their web pages. Furthermore, many of the companies had published a sustainability report. Also, successful tools to support the assessment of sustainable development are available (see Table 2). Nevertheless, application of these tools is not very commonplace in Finnish companies (as shown in Table 3). As earlier research has revealed, companies lack information and access to tools (see Häkkinen et al. 2013).

More importance should be given to bridging the gap between researchers who have knowledge of the tools and company managers who need support in their utilisation. One option for further development of the tools discussed in this paper is to create easy-to-use Web-based versions of these tools. There are several tools that can be downloaded without charge or be used on the Web (e.g. openLCA and the MCDA methods applied by SuperDecisions). There is, at least to our knowledge, no research on utilisation of these Web-based versions of the tools. Also, the reliability of these versions can be questioned. Nevertheless, these tools can yield some insights for company managers and at least provide learning experiences.

It is apparent that there is methodological expertise available to support sustainability assessments of companies and also that the companies are interested in sustainable development. Interviewing company managers could provide valuable information on their needs related to the assessment of sustainability. Also, semi-structured interviews could provide valuable information on the reasons why companies are not currently using many of the sustainability assessment tools addressed in this paper. Evidently, more information surrounding this topic is needed. In addition, the cooperation between experts and companies should be developed further. For instance, Judl et al. (2015) actualised a series of streamlined LCAs for SMEs. In their experience, the key issues in a product life cycle could be identified within 10–40 hours of research work, with only 8 hours of company involvement. Sustainability assessment trials of this sort, with the aim of generating an action plan that is feasible for an actual company, could be fruitful for both company-level decision-making and methodologically oriented research. In particular, SMEs would be suitable for such trials, as they do not have the resources and abilities to prepare the assessments without expertise.

3.5. Conclusions

Sustainable development and tools to support it have been extensively studied, but far fewer studies have investigated the actual company-level utilisation of these tools. The aim of our study was to address this central and timely issue. In summary, we systematically evaluated a sample of tools commonly used in research articles and found that none of the tools reviewed was comprehensive with respect to the assessment criteria. To meet the needs of sustainable development, some modifications to the tools are needed. Previous studies have shown that simultaneous use of several tools has substantial benefits. For example, MCDA requires input from other tools and methods, in order for reliable quantitative impact assessments to result. In our review of the web pages and sustainability reports of 39 energy companies, 20 hotels and restaurants, 20 mines and 48 construction companies for determining the state of utilisation, we found that Finnish companies seldom use any of the tools reviewed. Of the tools considered, sustainability indicators and indices were regularly applied, and only a few companies (in the construction sector) had used LCA. There is, evidently, a gap between research and companies, since the tools that are so often discussed in research articles are not used at the company level. It is apparent that, to bridge this gap, companies need more support with the utilisation of tools. One solution could be small-scale sustainability trials conducted by sustainability experts (e.g. members of research institutes or consultation companies specialising in relevant topics). Within these sustainability trials, companies could find ways to minimise their negative impacts on the environment and simultaneously gain potential economic benefits, without excessive investment of resources in sustainability assessment.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This study was conducted as part of the Towards sustainable economic systems – key methods and tools, lessons learnt and future outlooks (ToFu) – project funded by the Finnish Environment Institute (SYKE). In addition, the study was supported by the research project "Sustainable, climate-neutral and resource-efficient forest-based bioeconomy", funded by the Academy of Finland, Strategic Research Council (decision no 293380).

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Sustainability in manufacturing – relative and absolute perspectives[1]

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Abstract
A sustainable development meets the needs of current generations without compromising the abilities of future generations to meet their own needs. Manufacturing plays a central role in helping us meet our needs for food, mobility, housing etc. but which needs are we talking about and how do we ensure that our production activities do not compromise the need fulfilment of future generations? Stability of the climate and ecosystems is an essential precondition for the functioning of our societies, but while we have seen continuous improvements in the eco-efficiency of our technology (delivered service per environmental impact) over the last decades, we have also seen increasing pressure on our environment, and irreversible changes seem imminent if we don't change our ways. For manufacturing this means that we need to shift our focus from relative sustainability (the solutions we develop are more sustainable than what they replace) towards absolute sustainability (solutions that are sustainable – in absolute terms). For climate change the Paris agreement to strive for climate neutrality by 2050 is an example of an absolute boundary that defines environmental sustainability. But we are also in the middle of a deep biodiversity crisis that is caused by a range of other environmental impacts and also here manufacturing needs to orient itself towards technological developments that have the potential to meet the needs of present and future generations within the biophysical limits of our planet.

[1] This paper is a keynote for the 19th International Machine Toole Engineers' Conference IMEC2022 10-11 November 2022 in Tokyo, organised by the Japan Machine Tool Builders' Association. The paper is based on previous papers by the author to which the reader is referred for further elaboration, in particular [17] [15] [14]

The paper starts by laying the ground with a brief introduction of different definitions of sustainability and then goes on to discuss the sustainability challenge that faces us and the role that technology must play in order to meet the challenge. The need to distinguish between relative and absolute sustainability is introduced, and the paper concludes with a suggestion of a definition of sustainable manufacturing.

1. Sustainability definitions

The term is actually self-explanatory; an activity that is sustain-able is an activity that it is possible to sustain, in principle indefinitely, without the activity undermining itself.

From "Our Common Future to the World Goals

With the 1987 report 'Our common future', the Brundtland Commission, United Nations' Commission on Environment and Development, positioned sustainability centrally in the discussion of our development of the world. The report presented a definition of a sustainable development as a "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" [39]. With its focus on fulfilment of human needs now and in the future, the definition has been widely adopted since then, but the devil lies in the details, and the definition gives no specification of which type of needs are concerned: fundamental physiological needs for nutrition and shelter or also needs for higher levels of fulfilment? The Brundtland Commission report also introduced the point that a sustainable development at the same time must consider both the environmental dimension and the social and economic dimensions. This was operationalized in a business context by John Elkington in the following years with his suggestion of the three dimensions of sustainability reflected in three separate bottom lines (people, planet, profit) that a company should focus on balancing in order to be sustainable [7], as illustrated by Figure 1A.

Further detail was added to the picture in 2015 when the member states of the United Nations adopted the 2030 Agenda for Sustainable Development, specifying the three sustainability dimensions into 17 Sustainable Development Goals (SDGs) with a total of 169 underlying targets to be achieved before 2030 with the aim to "… end poverty, protect the planet and improve the lives and prospects of everyone, everywhere" [35].

Introducing absolute limits for sustainability

Around 1970, a group of researchers developed the first computer models of the developments in global human population, food production, industrialization, pollution and consumption of non-renewable natural resources and analysed future scenarios to investigate whether changes in the growth patterns for these five parameters might allow emergence of a sustainable feedback pattern for the human civilization. They found that one out of three analysed scenarios lead to a "stabilized world" while the other two scenarios lead to "overshoot and collapse" and reported their results to the Club of Rome and to the world in the report "*Limits to growth*" [24]. Their demonstration that there are absolute boundaries posed by Earth's finite natural resources and the limited capacity of the environment to absorb pollution was challenged at the time, but lately the existence of absolute boundaries for man-made pollution of the atmosphere with greenhouse gases has gained not just scientific-, but also broad political acceptance. This was demonstrated by the adoption of the *Paris Agreement* targets to keep our climate change impacts at a level where global atmospheric temperature increase remains close to 1.5 degrees above pre-industrial levels, and it reflects stronger sustainability definitions where the social and economic dimensions of sustainability are nested inside the environmental dimension and where the environmental impacts caused by fulfilment of human needs must respect the tolerances of the Earth systems, as illustrated in Figure 1B.

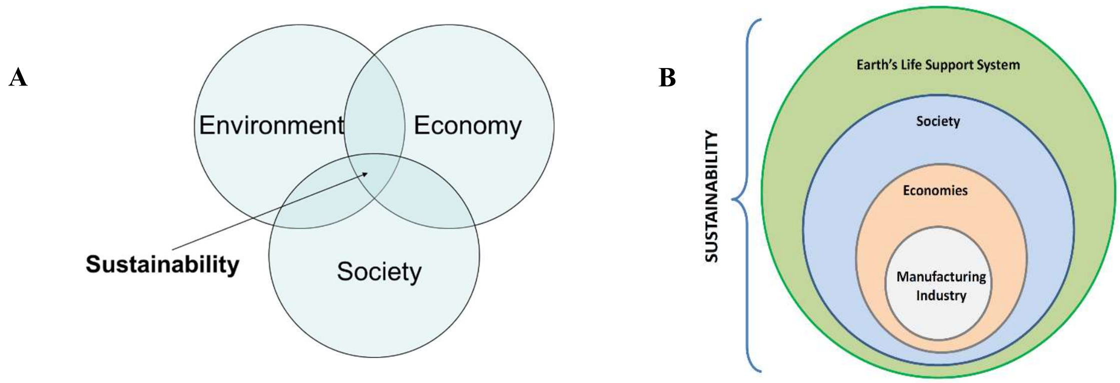

Figure 1. The three sustainability dimensions from triple bottom line (A) to absolute environmental sustainability (B) (from [15], based on [28]).

The *Science Based Targets Initiative* takes this global commitment to absolute limits for our climate change impact down to the level of individual companies by offering a reporting and monitoring system to support their commitments to voluntary reductions for their business and value chains [31].

Taking a broader perspective on climate stability, Rockström, Steffen and colleagues identified nine planetary environmental processes including the release of greenhouse gases to the atmosphere, use of land, and nutrient cycling, that they consider essential for the planetary self-regulation that ensures the stable environmental conditions that humanity has known since last ice age throughout the Holocene epoch [27] [33]. Building on natural science they proposed for each of the nine processes a "safe operating space for humanity" delimited by critical impact levels ("*Planetary Boundaries*") that we need to avoid exceeding in order not to jeopardize the stability of our natural systems. Out of the nine proposed planetary processes, they found that the boundaries have been exceeded for three.

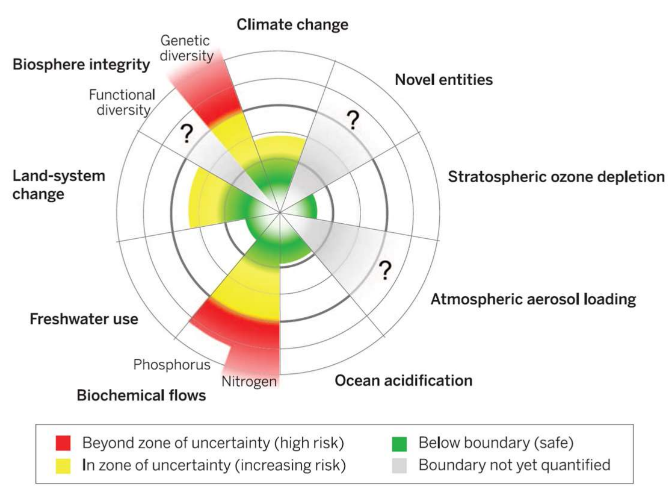

Figure 2. Nine planetary boundaries defining a safe operating space for humanity (from [33])

2. The sustainability challenge

To get an idea about the challenge that we are facing in order to meet the human needs and avoid exceeding environmental thresholds that may lead to serious environmental consequences, it is useful to perform a quantitative analysis of the developments in the main drivers behind the man-made environmental impact.

2.1 The IPAT equation

The IPAT equation (Eq. 1) was developed in the 1970's based on work by Ehrlich and Holdren [6] and Commoner [5] to analyze and focus attention on the key factors driving man-made environmental impact. It presents the total environmental impact (I) as the product of three central drivers viz. the human population (P), the human affluence (A, the material standard of living), and the technology factor (T, the environmental intensity of our technology expressed as environmental impact per created value or functionality)

$$I = P \cdot A \cdot T \qquad \text{(Eq. 1)}$$

When population and affluence grow, the environmental intensity of the technology that provides the affluence of the growing population must be reduced in order to avoid increased environmental impact. But by how much? What is the challenge that environmental sustainability of a growing consumption poses to technology?

The technology factor can be isolated from Eq. 1 as:

$$T = \frac{I}{P \cdot A} \qquad \text{(Eq. 2)}$$

Considering the example of climate change impact, the man-made emissions of greenhouse gases causing climate change (I) in 2030 needs to be roughly halved relative to 2020 levels to follow future emission trajectories from the Intergovernmental Panel on Climate Change that allow us to respect the 1.5°C temperature increase ceiling [20]. Over the same decade, the global population (P) is forecast to increase by a factor 1.1 [36]. The affluence (A) may be represented by the global economic gross domestic product (GDP) and over the last six decades global GDP has grown between 20% and 210% per decade [38]. Assuming a 30% increase in GDP from 2020 to 2030, the environmental intensity in 2030 can be calculated as:

$$\frac{T_{2030}}{T_{2020}} = \frac{{}^{I_{2030}}/_{I_{2020}}}{{}^{P_{2030}}/_{P_{2020}} \cdot {}^{A_{2030}}/_{A_{2020}}} = \frac{0.5}{1.1 \cdot 1.3} = 0.35 \qquad \text{(Eq. 3)}$$

This means that from 2020 to 2030 the overall average environmental intensity of our technology has to be reduced by a factor 3, in order to be on the track to keeping the global average atmospheric temperature increase at or close to 1.5 °C. This factor 3 is an average number across all technologies. Since some technologies will be seriously challenged to deliver such improvements over a decade, others will have to reduce more in order to reach this level of improvement overall. Requirements to improvements of 4, 10 or even as high as a factor 50 have previously been proposed, for varying types of environmental impact and reflecting different assumptions about time horizon and developments in population and affluence [8] [26] [30] [37].

2.2 T-factor and eco-efficiency and how to measure them

The ISO 14045 standard [21] defines eco-efficiency as an “aspect of sustainability relating the environmental performance of a product system to its product system value”. This author offers the following expression for calculating it [14]:

$$Eco-efficiency = \frac{value\ created\ or\ functionality\ provided}{Environmental\ impact\ caused} = \frac{1}{T} \qquad \text{(Eq. 4)}$$

With this definition, eco-efficiency is the inverse of the environmental intensity T.

A comparative LCA is focused on a functional unit that defines the function or service provided by the compared product alternatives in terms of type, duration and extent thus ensuring that when different product alternatives are compared in the LCA, they do provide the same service and are functionally equivalent for the user [13]. By thus fixing the functionality provided by the product, the numerator in Eq. 4 is constant for the compared alternatives, and taking a life cycle perspective while addressing all relevant impacts, LCA is the obvious tool for comparing eco-efficiencies of products and technologies [21].

The ISO standard [21] also argues that the environmental impact should be evaluated using Life Cycle Assessment (LCA). When the focus is on value creation through production and use of products, there are two good reasons to follow this ISO requirement:

The first reason is that the creation of value or function through products will cause impacts on the environment not just during the manufacture or use of the product but also through the acquisition of resources that are used to produce or operate the product. At the end of its use, the product may cause negative impacts through end of life treatments but the product may also be refurbished to have a second life or act as a source of materials or components for other products, thus saving additional production and hence having a positive impact. All these stages of the product’s life cycle must be considered to ensure that the calculated eco-efficiency gives the full picture of the environmental impacts that the product causes and to avoid problem shifting when reduced environmental impacts from one stage of the life cycle leads to increased impacts from other stages [16], [9].

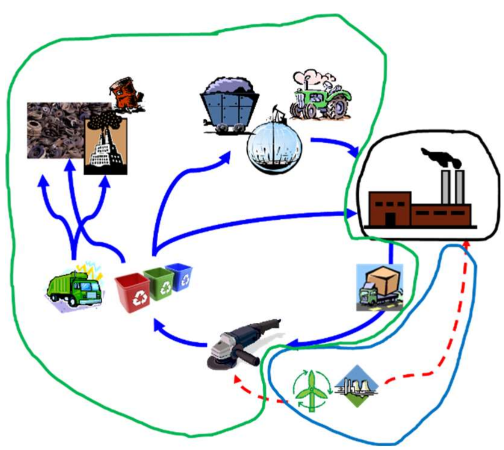

Figure 3. In eco-efficiency assessment a life cycle perspective should be applied on the activity

Figure 3 shows the life cycle of a hand tool and illustrates the three scopes for which the environmental impacts are typically quantified and reported. Scope 1 covers the company itself and the scope includes direct emissions from sources that are owned or controlled by the company. Scope 2 covers the company’s purchase of energy such as electricity, heating or cooling from external utility companies. Scope 3 covers the rest of the company’s value chain, i.e. suppliers and

their suppliers back to the raw material extraction, and including management of generated waste from - and transportation throughout - the value chain. An LCA covers the combination of the three scopes and assures that any problem shifting is revealed.
The second reason to use LCA for assessment of the environmental impacts in Eq. 4 is that products can cause contributions to many different environmental impacts ranging from the global scale with climate change, stratospheric ozone depletion and loss of non-renewable resources, over regional impacts like acidification, eutrophication, photochemical ozone formation and toxic impacts to humans and ecosystems, to local scale impacts like use and destruction of land and depletion of water resources. LCA offers a well-established methodology with a consistent and coherent framework of mutually exclusive and collectively exhaustive impact categories to assess and compare the contributions to all these impacts in a quantitative manner [12], [16].

3. From relative to absolute

Industry's focus on increasing energy-efficiency or eco-efficiency promotes development of products that offer more functionality per caused environmental impact or resource use. Gutowski illustrates this with the example of lighting technologies [11]. Examining the development from the early 19th century Ausubel and Marchetti find that the energy efficiency of lighting technologies has undergone an exponential development, increasing more than two orders of magnitude from the paraffin candle to recent diode lamps [1]. Today, a given lighting service can thus be obtained with a minimal fraction of the energy used two centuries ago. Investigating human consumption of lighting, Tsao and colleagues show that despite the dramatically increased energy efficiency, the share of our purchasing power spent on energy for lighting has remained remarkably constant over the same period [34]. Since the purchasing power has grown dramatically over the last centuries, so has the use of energy for lighting over this period, despite several orders of magnitude increase in the energy-efficiency of lighting sources. Increased energy-efficiency might have been expected to support a decoupling between consumption and environmental impacts for lighting services, but this is not observed – on the contrary. Higher energy-efficiency also means reduced costs of lighting, and this inspires an increase in the use of lighting. This coupling is referred to as a rebound effect in the market, and in the case of lighting, it more than neutralizes the efficiency gains. Instead of a decoupling, an increased use of electricity is observed in what environmental economists call a backfire effect [18].
Examining 57 cases of technological efficiency improvement covering different materials and technologies over the last decades, Magee and Devezas demonstrate that it is a general observation that rebound effects counteract technology efficiency improvements, and they are not able to demonstrate in any of the investigated cases that the achieved efficiency improvements lead to reduced resource consumption or environmental impact [23]. This observation is confirmed when taking a top-down perspective on the development in the environmental impact that our societies have caused globally over the last centuries. Steffen and colleagues map trends in earth system impacts like loading of the atmosphere with the main greenhouse gases CO_2, CH_4 and N_2O, loading of coastal waters with nitrogen compounds, loss of stratospheric ozone due to man-made emissions of persistent halocarbons, and degradation of the terrestrial biosphere [32]. All trends show strong increases after 1950 and for some of them the trend approaches an exponential development. These environmental impact trends mirror central socio-economic trends like growth in population and urbanization, and growth in GDP, and trading of many fundamental commodities.

3.1 From better to good enough – we need to introduce an absolute perspective

The analysis of the IPAT equation in Equations 2-4 assumed that A and T are independent, but in reality this is rarely the case, since increased eco-efficiency often leads to a growth in consumption and affluence, as discussed above. While a strong increase in the eco-efficiency of products and technologies is clearly needed to ensure a sustainable level of environmental impact, the examples illustrate that a focus on eco-efficiency alone is insufficient to ensure a future sustainable consumption and production. There is a need to analyze the overall outcome in terms of environmental impact for a product or technology and relate it to the share of the operating space that this product or technology can claim, e.g. considering the size of its market, to ensure that the improvement leads to solutions that are not just more sustainable than what they replace, but sustainable in absolute terms [14].

Bjørn and Hauschild introduced the absolute sustainability perspective into the field of product assessments [2]. They showed how absolute boundaries at the level of companies or even individual products may be derived from the boundaries presented by the Planetary Boundary framework or from other science-based bio-physical boundaries for man-made environmental impact that define a total pollution space that must not be exceeded [3] [4]. The pollution space can be considered a restricted resource similar to the limited natural resources for which societal actors compete. Determination of which share of the space (environmental or resource), an individual country or company can claim, requires an allocation of the total space. While there is good agreement on the principles for a science-based determination of the boundaries and of a safe operating space (noting that the methods for this are still under development), the allocation of the space between actors is still in its infancy [22]. The Science-Based Targets initiative presents the "grandfathering" principle according to which the companies have to reduce their total emissions of greenhouse gases by the same percentage, reflecting the reduction that is needed for society as a whole [31]. Assuming that the right to use the pollution space belongs to human individuals, the available space may also be allocated among countries according to their population sizes as done by Nykvist and colleagues in their assessment of which nations stay within their share of the safe operating space delimited by the planetary boundaries [25] and by the Global Ecological Footprint Network in their calculation of ecological footprints for nations [10]. Alternative allocation approaches were tested by Ryberg and colleagues [29] demonstrating their influence on the absolute sustainability assessment of the service of laundry washing in Europe. Figure 4 shows the dependency of the outcome on the choice of allocation principle.

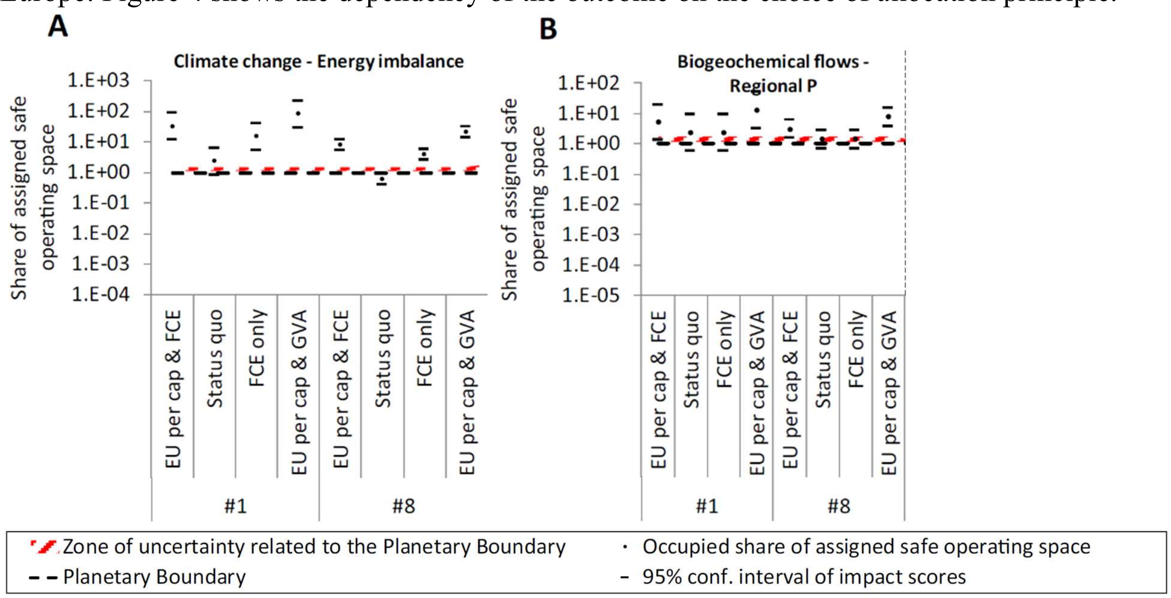

Figure 4. Absolute sustainability of European laundry washing considering climate change (A) and freshwater eutrophication through emissions phosphorus (B) under current conditions (#1) and in a potential future scenario involving eco-efficiency improvements in energy system, washing practices and sourcing of detergent ingredients (#8). Four different allocation approaches are applied for each scenario. When the occupied share of the assigned safe operating space exceeds 1, the scenario is unsustainable (from [29]).

Hjalsted and colleagues [19] proposed a method for assigning shares of global or regionally determined safe operating spaces to the level of the individual and then upscaling them to the level of a country, sector or product and analyzed different ethical principles for performing the allocation and upscaling (see Figure 5)

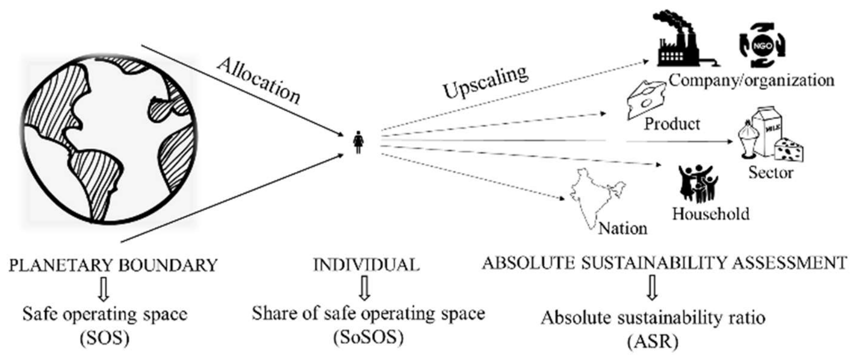

Figure 4. Sharing safe operating space between different actors [19].

Figure 5. A two-step approach to allocate a global safe operating space to different organization levels and activities

3.2 Sustainable manufacturing

All manufacturing causes impacts on the environment through its use of materials and energy and potential releases of emissions to the surroundings. These impacts have to be justified by positive social contributions helping to meet needs of humans. It is therefore not meaningful to talk about sustainability of manufacturing in isolation. Manufacturing has to evaluated together with the utility of the products or services that it provides and this is also why UN Sustainable Development Goal number 12 is to ensure sustainable consumption and production patterns [35]. Sustainability of manufacturing should thus be determined by whether it contributes to sustainable consumption by providing products or services that are needed to support a sustainable lifestyle at large. With this as anchor point, we can develop the following definition of sustainable manufacturing:

Sustainable manufacturing is manufacturing that helps us meeting the needs of present and future generations within the tolerance levels of our planet's regulating systems (climate and ecosystems).

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Making the transition to a Circular Economy within manufacturing companies: the development and implementation of a self-assessment readiness tool

Pigosso, Daniela C.A.; McAloone, Tim C.

Published in:
Sustainable Production and Consumption

Link to article, DOI:
10.1016/j.spc.2021.05.011

Publication date:
2021

Document Version
Publisher's PDF, also known as Version of record

Sustainable Production and Consumption 28 (2021) 346–358

Contents lists available at ScienceDirect

Sustainable Production and Consumption

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

Research article

Making the transition to a Circular Economy within manufacturing companies: the development and implementation of a self-assessment readiness tool ☆

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ARTICLE INFO

Article history:
Received 24 February 2021
Revised 16 May 2021
Accepted 17 May 2021
Available online 27 May 2021

Editors name: Prof. Adisa Azapagic

Keywords:
Circular economy
Readiness
Manufacturing companies
Transition
Tool

ABSTRACT

Circular Economy (CE) is a key approach to supporting a transition towards sustainable growth. However, due to the lack of understanding of readiness for the CE transition, manufacturing companies still face a number of challenges in successfully implementing CE. This paper describes the development of a CE readiness self-assessment tool, *MATChE* (MAking the Transition to a Circular Economy), following iterative cycles of theoretical development and empirical co-development with potential users. The resulting web-based platform enables a self-assessment of manufacturing companies' readiness to transition to CE. In addition to allowing the understanding of strengths and gaps for CE implementation across eight key dimensions (e.g. strategy and business model innovation), the tool enables internal and external benchmarking studies (at the company or business unit levels); the prioritisation of focus areas based on strategic drivers; and the development of transition paths with support of CE-related tools, methods and approaches. The MATChE tool is, at the time of writing, supporting over 330 manufacturing companies (incl. 900+ users), spread across 16 manufacturing sectors and 38 countries. Future research is ongoing to minimise the limitations of the tool and expand its scope beyond manufacturing companies, in a number of different directions (e.g. service providers and waste management companies).

1. Introduction

The increasing recognition of the need to mitigate the effects of population growth, wealth increase and human consumption is currently leading several international organisations, such as the European Union (EU) (European Commission, 2019), the Organisation for Economic Co-operation and Development (OECD) (Steffen et al., 2015; OECD 2018, 2019) and the United Nations (UN) (UN, 2020), to consensually highlight the need for a significant change in our economic system, in order to respect the planetary boundaries (Steffen and Stafford Smith, 2013; Häyhä et al., 2016). In this context, Circular Economy (CE) has emerged as a key approach to support sustainability transition and enhance industry competitiveness, towards sustainable growth (European Commission, 2020). CE is defined as "an economy that provides multiple value creation mechanisms, which are decoupled from the consumption of finite resources" (Ellen MacArthur Foundation, 2015b), which is particularly relevant within the context of manufacturing companies (Pieroni et al., 2021a; Lieder and Rashid, 2016). A successful transition to CE requires a systemic change in the way companies understand and do business, with sustainability as a strong foundation (Kravchenko et al., 2019; Millar et al., 2019).

Currently, industry is faced with a duality of opportunities and challenges (Hopkinson et al., 2018), as described in the following. The potential sustainability and business benefits from adopting a circularity mindset in industry are significant. In Europe alone, the business benefits linked with CE are estimated to be ca. 1.8 trillion Euro per year up until 2030 (Ellen MacArthur Foundation, 2015b). Nevertheless, despite the increased interest in CE implementation and the large amount of research and governmental incentives (van den Bergh, 2020), companies still face challenges in successfully implementing CE (Bocken et al., 2016). Once having decided to implement CE, the key challenges faced by manufacturing companies are connected to:

- Systemic nature: creating a CE requires fundamental changes throughout the value chain (Bressanelli et al., 2020), from new business model innovation (Galvão et al., 2020), product/service design (Blomsma et al., 2018; Pigosso et al., 2014) and production processes all the way to consumption patterns

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https://doi.org/10.1016/j.spc.2021.05.011

(Geissdoerfer et al., 2020) and end-of-life scenarios (EEA, 2016; Hopkinson et al., 2020).
- High complexity: new uses of existing material flows increases the boundaries and the complexity of CE systems (Korhonen et al., 2018). Furthermore, the evaluation of the sustainability performance of CE systems presents high complexity (Kjaer et al., 2019; Rodrigues et al., 2017).
- High risks: the systemic nature and high complexity of CE also leads to high risks in the implementation of CE businesses (Trigkas et al., 2020). Furthermore, a number of risks associated with managing hazardous substances in a circular system exist (Bodar et al., 2018).
- Multi- and inter- disciplinarity: the complexity and novelty of CE requires the combination of a number of disciplines, such as natural sciences, engineering, business, economics and management (Sauvé et al., 2016), which takes extra effort to orchestrate.
- Lack of knowledge: a successful CE implementation in companies requires new knowledge, capabilities and skills (e.g. ranging from material composition to social behaviour) (De los Rios and Charnley, 2017; Kalar et al., 2021).

The aforementioned challenges are mostly experienced by companies that have already decided to investigate the potential of transitioning for a CE, which correspond to the main scope of this research. Nevertheless, it is important to highlight that the existence of other business-oriented challenges (e.g. economic barriers, value chain barriers, legal barriers, risk barriers (Rizos et al., 2016)), as well as theoretical challenges (e.g. as the lack of a consistent CE definition (Kirchherr et al., 2017), incl. social and cultural definitions of waste (Korhonen et al., 2018)), also play an important role in hindering the transition to CE.

Manufacturing companies play a key role in CE implementation, due to their strong contribution to the economy and significant influence in creating, delivering and capturing value from new products and services across the entire value chain (Pieroni et al., 2021b). It is estimated that only 2-5% of companies have currently successfully implemented circular business models (OECD, 2018). The *circularity gap* (measured in terms of the share of virgin materials in relation to the total material consumption, based on the System of Environmental-Economic Accounting) is currently growing (de Wit et al., 2020), indicating that CE is still insufficiently implemented worldwide.

Momete states that the limited implementation of CE might be linked to a lack of analytical diagnosis tools, which could offer the big picture about the readiness of companies and economies to migrate from an unstainable linear model to a sustainable circular one (Momete, 2020) On the one hand, the lack of understanding of the companyś readiness before starting out on the journey towards CE leads to a higher chance of failure during the implementation (Zhang et al., 2020). On the other hand, the assessment of readiness before heavily investing resources into the necessary change process is known to increase the probability of success of initiatives (Rodgers et al., 2021) and ensure a more effective implementation of complex changes (Weiner, 2009).

To address these challenges and enhance the potential success of CE implementation in manufacturing companies, this paper describes the development of a CE readiness self-assessment tool, *MATChE* (MAking the Transition to a Circular Economy), which aims to deliver four elements of support for CE transition within manufacturing companies:

(i) understanding strengths and gaps for CE implementation.
(ii) perform internal and external benchmarking.
(iii) prioritise focus areas.
(iv) plan transition paths with support of CE-related tools, methods and approaches.

The next section (Section 2, Literature review) describes the theoretical foundation for readiness assessment, highlighting existing studies tackling CE readiness at different levels of analysis. It is followed by a detailed description of the scientific approach employed for the development of the tool (Section 3, Methods), including the theoretical development based on state-of-the-art review within readiness assessment approaches, as well as strong stakeholder engagement for the empirical co-development through action research and case studies, aimed at enhancing the tool's usefulness and usability. Section 4, Results, presents the final version of the tool, its key features and the key steps taken for its application. The key findings are further discussed in Section 5, Discussion. Finally, the key limitations and potential future research are highlighted in Section 6, Conclusion.

2. Literature review

The concept of organisational readiness for change is explored by a number of different disciplines, such as management, health, information technology and engineering (Weiner, 2009). Organisational readiness is defined as a comprehensive attitude that is influenced by four main areas: the content of the change (i.e. 'what'); the change process (i.e. 'how'); the context of the change (i.e. 'where'); and the individuals involved in the change (i.e. 'who') (Holt et al., 2007). In that sense, the readiness concept refers to "the state of being both psychologically and behaviourally prepared to take action (i.e., willing and able)" (Weiner, 2009).

Readiness assessments aim to provide a systematic analysis of an organisation's ability to change and transition to a new desired state (Jöhnk et al., 2021), with an indication of opportunities, gaps and potential challenges (Pirola et al., 2019). The readiness assessment can be performed through qualitative (i.e. interviews and observation) or quantitative (i.e. surveys and questionnaires) approaches, and special emphasis should be given to the reliability and validity of the results (Holt et al., 2007). By assessing the readiness level, companies can get a situational analysis of current readiness, as a starting point for prioritising action. The current readiness can also be used as a benchmark for comparison, to support the transition process (Pirola et al., 2019). Studies have also demonstrated the relevance of readiness assessments within complex changes, involving one or more organisations (Blackman et al., 2013), as a precondition for innovation (Halpern et al., 2021), and as the best early indicator of how organisations will respond to introducing new business systems (Ochurub et al., 2012).

Within the broad CE literature, initial studies focused on readiness assessment on numerous levels, including: at a country level (Momete, 2020; Garcia and Cayzer, 2019); at a sectorial level (Siew, 2019); at an ecosystem level (Parida et al., 2019); at the regional level (Pigosso et al., 2018); and at the level of individual readiness of employees (Singh et al., 2018), as following described.

In 2019, Garcia and Cayzer (2019) proposed the assessment of CE transition readiness at a national level, demonstrated in a Colombian case. The framework contains a combination of top-down (i.e. policy and legislation, supportive infrastructure and awareness) and bottom-up enablers (Information and communications technology (ICT) and Business models Design & Supply Chain) (Garcia and Cayzer, 2019). One year after, Momete (2020) proposed a unified framework for assessing the readiness of European Union economies to migrate to a circular modelling, based on the evaluation of the three sustainability pillars (i.e. economic, social and environmental). In addition to enabling benchmarking at a country level, the framework also supported the identification of systemic interventions needed by the EU in the path towards circularity.

Siew (2019) evaluated the readiness for CE in the construction sector in Malasya based on a survey questionnaire with 100+ respondents. The survey measured the CE readiness in the sectorial level based on the evaluation of five indicators (i.e. input in the production process, utility during the use phase, destination after use, efficiency of recycling and complementary risk indicators), following a Likert scale ranging from 1 (not ready) to 5 (extremely ready) (Siew, 2019). At an ecosystem level, Parida et al. (2019) developed a two-stage transformation model for orchestrating industrial ecosystems in CE. The ecosystem readiness assessment evaluates trends and regulatory trends across three areas: (i) the external environment, (ii) business model, and (iii) ecosystem partner (Parida et al., 2019).

At the regional level, Pigosso et al. (2018) propose the evaluation of the readiness for industrial symbiosis collaborations across co-located companies in a given region , actively supported by the involved municipalities. The readiness is evaluated using a 10-point Likert scale across ten different areas: resource minimisation potential, reuse/recycle potential, change of raw materials potential, waste commercialisation potential, potential for business model innovation, investment potential, readiness to cooperate and communicate, readiness for knowledge sharing and experience in managing trade-offs. Finally, at the level of the individual employees, Singh et al. (2018), developed an extended theory of planned behaviour model considering attitude, social pressure, perceived behavioural control, environmental commitment and green economic incentives (Singh et al., 2018).

Despite the range of existing readiness approaches listed here, no readiness approaches address the company organisational level, which is fundamental for supporting the transition to a CE. Furthermore, none of the approaches identified follow a life cycle perspective, and none of them provide the possibility to perform a benchmark with other (internal or external) business units, nor do they couple these to advice regarding how to make a transition to CE, based on their identified readiness.

3. Methods

Assisting companies within the manufacturing sector to assess their readiness to transition to CE must take point of departure in the relevant knowledge within the field, to the context of a typical manufacturing company. For this reason, the development of the MATChE CE readiness self-assessment tool was carried out based on a strong methodological approach, in order to ensure: (i) the inclusion of relevant dimensions to the industry branch; (ii) the inclusion of state-of-the-art science-based knowledge from literature, following the systematic literature review method (Biolchini et al., 2005); (iii) a transparent, verified and validated process to the development of the tool based on action research (Coughlan and Coghlan, 2009) and case studies (Yin, 2006) methodology; and (iv) a repeatable and updatable tool design, allowing for later adaptations, to other industry fields than the manufacturing industry.

To ensure the above quality dimensions in the design and development of the MATChE self-assessment readiness tool, three development cycles were applied before launch (Fig. 1).

3.1. Cycle 1: theoretical development

The first step in the MATChE tool development process was to carry out a literature review, to firstly ascertain important success factors, drivers and barriers for company transition to CE. As the field of CE is relatively young, related studies regarding the adoption of sustainability strategies in general were also studied in the literature review. Two main enquiries were developed in the literature review, to enable the first iteration of the readiness assessment tool, namely: (i) literature regarding readiness assessment approaches, to inform the definition of readiness steps (Section 3.1.1); and (ii) literature regarding necessary dimensions for manufacturing companies to master, when working with CE (Section 3.1.2).

3.1.1. Developing a readiness scale

To elicit literature regarding readiness assessment approaches, an iterative process was applied to develop the following search string in Scopus: *TITLE (readiness) AND TITLE-ABS-KEY ((transition OR "change management") AND (organi?ation*) AND (scale OR measure OR evolution OR likert)).* The search in Scopus resulted in 28 relevant papers, which were further evaluated in relation to the following inclusion criterion *"papers should include the definition of a scale for measuring organisational readiness"*, resulting in nine papers being finally selected. A common characteristic of the majority of the identified studies was that they used a five-point Likert-scale (e.g. ranging from 1 (strongly disagree) to 5 (strongly agree) (Haffar et al., 2014; La Lopa and Day, 2011; Zephir et al., 2007), adapted to their specific aims (e.g. the ability of performing a given task; from not being able to perform a task to being able to support others to perform a task) (Wijnen-Meijer et al., 2012). On the basis of the scales derived from the literature study, the generic five-point Likert scale was decided, spanning: "1 – Not ready; 2 – Low readiness; 3 – Medium readiness; 4 – High readiness; and 5 – Ready". A frequent challenge with generic Likert scales is that they can be subject to multiple and inconsistent interpretations, thus essentially rendering them unusable, not least if they are to be used for benchmarking. For this reason, the readiness scale was customised for the CE self-assessment, as described in Section 4.1.

3.1.2. Developing readiness dimensions and aspects

Gaining an understanding of the necessary dimensions of importance for CE transition was a more involved process, taking point of departure in a comprehensive review of literature to identify circular economy dimensions and aspects reported in the literature. Given that the field was subject to significant scientific and societal (grey literature) attention at the time of development of the readiness self-assessment tool, key systematic literature reviews (Lieder and Rashid, 2016; Tukker, 2013; Ghisellini et al., 2016; de Jesus et al., 2016; Heshmati, 2017; Masi et al., 2017; Liu et al., 2017) on circular economy formed the basis of the review of the scientific literature, whereas material (white papers, reports) from the European Union (European Commission, 2015), Ellen MacArthur Foundation (Ellen MacArthur Foundation 2015b; Webster, 2015; Ellen MacArthur Foundation 2015a, 2012, 2013b, 2013a) and SITRA (SITRA, 2016), the key organisation behind the World Circular Economy Forum, formed the point of departure for the grey literature. The following search string was used in Scopus as a starting point for the literature review, to elicit CE dimensions and aspects of importance to consider for industry, when transitioning to CE: *TITLE (("circular economy" OR circular?) AND (implementation OR transition OR change OR practice OR business OR application OR pursuit OR deployment OR execution))*, resulting in 82 documents. From these, the papers which presented business processes or life cycle areas of relevance and particular activities, achievements, or initiatives were selected; resulting in 61 relevant articles.

3.2. Cycle 2: low-definition prototype for expert testing

On the basis of the 61 identified articles in the literature review, five initial CE dimensions were identified, covering: organisational readiness; business model readiness; market readiness; (product and service) offerings readiness; and operations readiness. Each of the five CE readiness dimensions were detailed according to five CE aspects, summing up to 25 formulated CE readiness questions for the first prototype of the readiness assessment tool.

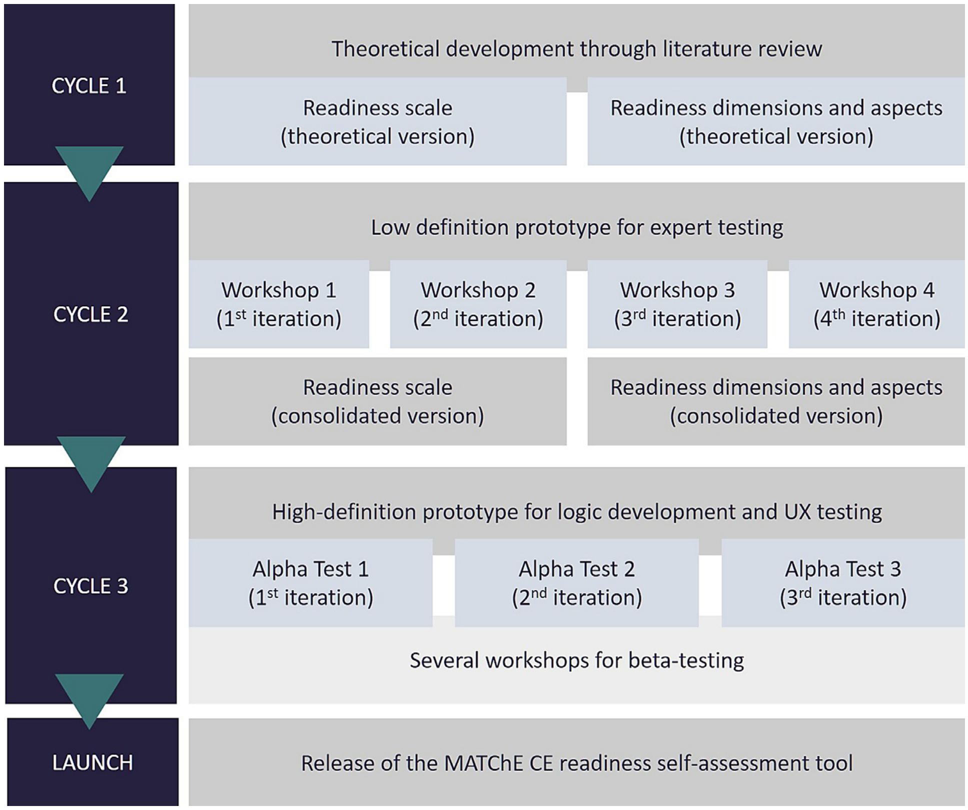

Fig. 1. Overview of the main cycles and steps carried out for the development of the MATChE CE readiness tool.

Fig. 2. (a) First low-definition (paper-based) prototype of MATChE CE readiness assessment tool; (b) workshop 2 with 35 environmental directors from Danish industry.

The low-definition prototype of the CE readiness tool was prepared as a paper-based prototype, with the intention of testing among experts (Fig. 2a). A paper-based prototype was purposely chosen to ensure focus on the contents and logic of the self-assessment tool, and not the user interface or functionality, which were not in focus here.

The low-definition prototype was subjected to four iterations, based on expert feedback in four controlled workshop environments. In total, 75 potential users of the tool were involved in the workshops, as further described. The participants could freely choose what would be the input context for the self-assessment (e.g. the entire company or a specific business unit), to allow for a broader test of the tool. In all workshops, data regarding the readiness assessments performed by the participants were not shared with the researchers, as the workshop process was designed to collect feedback regarding the dimensions, questions, and the readiness scale (and not the readiness results). Furthermore, the involved participants were fully aware of the stage of the research, and the inherent limitations in relation to the quality of the output data to support decision-making. The low-definition prototype was enhanced from one workshop to the next, enabling an iterative development and test of new features and elements (i.e. the final workshop corresponded the test of the third iteration of the low-definition prototype which was enhanced after the first workshop (1st iteration), second workshop (2nd iteration) and third workshop (3rd iteration) – resulting in the development final 4th iteration.

The first workshop aimed to test the low-definition prototype amongst 15 Life Cycle Assessment (LCA) and ecodesign experts from Danish companies, all operating at the 'specialist' level in their respective companies (including ARLA, Novo Nordisk, Coloplast, Danfoss, Grundfos, LEGO Group, etc.). This workshop reaped very detailed feedback on the readiness scale, the aspects presented and highlighted key gaps in the dimensions and aspects, leading to a new version of the prototype, with adjusted dimensions and aspects. The test population within the workshop were an important reference for the process, as they were members of a closely collaborating open industry interest group, within which the authors were also a member, leading to high trust and therefore direct and honest feedback. The respondents represented mostly the tactical and operational layers of their respective companies.

The second workshop enabled the test amongst 35 sustainability and environmental managers and directors from 35 Danish companies, as part of the Confederation of Danish Industry's Director Forum for Environmental Affairs (Fig. 2b). This workshop, presenting the second iteration of the tool, brought new insights into the necessary iteration of the tool development, due to: (i) it's presentation to potential users at the tactical (management) and strategic (director) levels of companies; and (ii) a broader reach to companies from numerous sectors (heavy industry, electronics, butchers, medico, construction, fast moving consumer goods, etc.). The feedback gained from this workshop uncovered the need to include a more market-oriented view, a consideration of policy drivers and barriers, and a more astute focus on the organisational aspects of CE transition.

In the third workshop, the CE readiness self-assessment prototype was tested amongst 25 sustainable product development researchers, within the authors' own research network. This workshop ensured an expert-critical view on particularly the aspects and dimensions of the CE readiness assessment tool, questioning of the need for an equal amount of aspects covered under each dimension, and pointing out gaps and overlaps between some aspects. A thorough re-work of the dimensions and aspects was the main outcome of this workshop.

Finally, the fourth workshop involved a new test amongst the 15 LCA and ecodesign specialists from Danish companies (same group as workshop 1), in order to verify and validate changes and developments applied since the first iteration. This workshop saw the last iteration of the paper-based prototype, which gained positive feedback regarding the new organisation of dimensions and aspects, but added a further dimension of 'Technology and Data', to capture the importance of the Internet of Things (IoT) and data-driven solutions to CE. The low-definition prototype resulted in an extensively iterated and validated concept for the CE readiness assessment tool, with a total of eight CE dimensions and 30 aspects (questions) and further described in Section 4.1.In addition to enabling the consolidation of a robust and industry-relevant set of dimensions and aspects, Cycle 2 also supported the definition of key features for the development of the MATChE tool:

(i) Assessment of CE readiness at different levels in the organisation (i.e. both at the company and the business unit levels): this feature is especially relevant for large organisations with different readiness across different business units.
(ii) Company-wide assessment, enabled by the possibility of engaging colleagues from different functions, covering a diverse skill set: this feature has been deemed relevant due to the need for cross-functional collaboration, avoiding the bias of just one representative within each company providing an often narrower view of the company's readiness.
(iii) Benchmark within the organisation, both internally (across different business units) and externally (with companies from similar sectors, regions and/or sizes): this feature is relevant to create the sense of urgency and alignment required for the CE transition.
(iv) Support for the development of transition paths, so to support companies in the prioritisation of the most relevant dimensions/aspects and the identification of the most relevant tools and methods to support the transition.

The aforementioned features were transformed into a requirements list and served as a key input for the development of the high-definition prototype, in Cycle 3.

3.3. Cycle 3: high-definition prototype for logic development and UX testing

On the basis of the identified requirements for the CE readiness self-assessment tool, the second prototype of the tool was built as a digital *'works-like, looks-like'* prototype. The tool was programmed from the bottom-up as PHP-based web-platform, on a secure server, to ensure data security for the later development of the final tool.

The web-based prototype of the MATChE CE readiness self-assessment tool consisted of a fully operational version of the tool, which included not just the contents of the CE dimensions and aspects, but also the logic behind the scoring of individual readiness levels and combined readiness levels of multiple contributors from the same organisation.

The logical flow development behind the tool was designed to encourage high quality and robust data from the users, in order to: (i) provide a transparent and trustworthy presentation of the readiness score for the company or the business unit being assessed; and (ii) ensure good conditions for the analysis of the delivered data through the resulting tool.

In preparation for the development of the web-based prototype of the tool, a study of the user experience (UX) design was carried out, by following a User Centred Design methodology (Abras et al., 2004), and entailing extensive user-journey mapping (Patton and Economy, 2014), storyboarding and user interface design (Saffer, 2013). This element of the development of the tool will not be detailed or discussed in any further detail, within this paper. The high-definition prototype was subjected to iterations in alpha-version and beta-versions (King et al., 2017). The three iterations of the alpha-version of the tool entailed the following test procedures:

- Test 1: Initial testing of the tool with 22 internal research colleagues (professors, researchers, PhD students, admin staff), to ascertain the reliability, usability and user journey experience of the tool. This test revealed many implicit shortcomings of the tool that were based on the authors having taken certain usability aspects for granted, which other colleagues did not quite catch.

- Test 2: Volume testing among three classes, ranging from 40-70 masters students, in order to: ‘stress-test’ the tool, regarding its usability within given scenarios; test its ability to act as an aggregator of multiple inputs; and test the integrity of the server, when receiving multiple responses. These tests gave many insights into the need for a more simplified user journey, and significant improvements in the registration and identification process, which posed teething troubles in the start. Tests within this group were repeated multiple times, on a voluntary basis by the students.
- Test 3: Alpha testing within the 15 LCA and ecodesign specialists (same group from ‘low-definition’ workshops 1 and 4), to ascertain feedback, regarding the digitisation of the tool, based on their earlier experiences and advice. The feedback from these trusted colleagues was invaluable, due to their extended prior investment into the testing of the tool. The tool was also released to these colleagues for test and feedback with their respective companies, either as facilitators themselves, or in collaboration with the authors.

On the basis of the three iterations in alpha-version, the project moved to the development of a beta-version, for own-use when facilitating workshops with single or multiple companies present.

The beta-testing of the tool was achieved through 20 workshops, in numerous constellations, ranging from single-company workshops (with between 15-80 delegates), to branch organisation workshops (often around 30 delegates from 30 companies), and many other setups, in between. The main learnings, at this stage, were about the reliability of the software platform for the tool, which needed to be upgraded to a dedicated server, in order to be able to cope with numerous simultaneous users, without experiencing server time-outs. After various iterations – and around 300 registered users on the tool’s web platform – a full release of the tool (for standalone usage) was announced.

The detailed self-assessment approach for CE readiness is further described in the Section 4.1, which contains the step-by-step approach for the CE readiness self-assessment and key features, as well as the detailed description of the final dimensions and questions. The application in a real world setting by users is exemplified in Section 4.2, which described the current user status of the tool and provides as exemplary demonstration.

4. Results

The resulting ‘MATChE CE readiness self-assessment tool’, from the research, assessment, prototyping and co-development process, is a stand-alone tool that can help manufacturing companies to carry out a self-assessment of its readiness to transition to CE.

4.1. Step-by-step approach for the CE readiness self-assessment and key features

The MATChE CE readiness self-assessment tool supports a ten-step approach, which starts with the identification of the current readiness profile and evolves towards planning the implementation and CE transition process (Fig. 3):

Step 1 starts when the user creates a user profile in the MATChE tool (www.matche.dk). The tool works by recognising the domain of a user’s email address (e.g. “@companyname.com”) as the identifier for the company to which the user belongs. The first time a new domain name is registered by a user, the ‘parent user’ will be asked to provide basic details of the company, such as a company name, primary sector, market type (business-to-business (B2B), business-to-consumer (B2C), business-to-government (B2G)), size, country, etc. These data are subsequently verified by the research team maintaining the tool, who further enhances the company profile by applying a specific company sector code, according to the Danish industrial classifications code “Dansk Branchekode 2007 (DB07)” (Statistikbanken, 2020), which is the national classification system based on the “Statistical Classification of Economic Activities in the European Union: NACE rev. 2” (Eurostat, 2008). All subsequent users with the same email domain will be associated with the same company, to enable them to contribute to the same readiness assessment(s). Clustering of multiple domains (i.e. for large holding companies with many sub-brands) is also possible, but from the tool administrator side, only.

It is important to highlight that not all users on the MATChE tool are within the intended scope of ‘manufacturing companies’; in fact, at the time of writing about 1/3 of all users belong to ‘out-of-scope’ organisations, i.e. non-manufacturing companies, service companies, consultancies, universities, government agencies, etc. Whilst it is important, from a research perspective, to keep the data in the platform used for benchmarking and statics ‘clean’, the authors also recognised that the readiness assessment tool and its related tools would be of high interest to ‘out-of-scope’ users. It was therefore decided to make the tool available to out-of-scope users, but to: (i) exclude the data entered by an ‘out-of-scope’ user from the statistics calculations; and (ii) disable an out-of-scope user from carrying out an external benchmark from among the ‘in-scope’ companies on the tool.

Step 2 involves the selection of the scope for the readiness self-assessment (i.e. the entire company or a specific business unit). By default, the CE readiness assessment tool establishes a ‘company level’ readiness profile. Based on the recognition, however, of the fact that a given company might have numerous business units, which might have differing levels of CE readiness, the tool allows for the unlimited creation of business units by the user, where all company participants on the tool can contribute to one or more business unit and/or the ‘company level’ readiness assessment. The MATChE tool aggregates the readiness scores from business units up to the company level readiness score, whilst also maintaining a readiness score on the basis of each business unit.

The user then answers the 30 readiness questions, across the eight CE readiness dimensions (Step 3), using the readiness scale designed according to the Likert system, with descriptors that enable a uniform answer from each respondent: 1: Understanding the potential; 2: Planning pilot implementation; 3: Piloting initiatives; 4: Planning scale up; and 5: Scaling up initiatives. The MATChE CE readiness self-assessment tool comprises a total of 8 CE dimensions and 30 aspects (questions), following combined business process and life cycle perspective (Table 1).

In Step 4, the user is required to define their skills and expertise areas, which will be used for calculating the robustness of the self-assessment. The tool has an in-built feature of recording expertise areas of each user. The expertise areas that the user can rate themselves on are: Maintenance and after-sales; Sales and marketing; Supply chain management and operations; Sustainability; Product and service innovation; Change management; Market intelligence & business development; Reverse logistics and waste management; Compliance, standardisation and lobbying. By rating themselves on a 1-5 Likert scale for each of these nine areas, the user contributes to painting an overall picture of ‘skills coverage’ for their company’s readiness assessment profile, which in turn encourages the invitation of sufficient colleagues to complete the CE readiness assessment, thus increasing the trustworthiness of the data. At the same time, these expertise areas tell a story, for the data analysis, of the types of users that are using the tool.

The analysis of the consolidated readiness results for the selected scope is performed in Step 5. To provide an overview to the user, of how much the current readiness score can be trusted, five indicators are included in the results view of the readiness as-

Table 1
CE readiness dimensions and aspects (questions).

Organisation
Readiness of 'Organisation' measures the internal business capabilities of your company to be able to implement new concepts, such as the Circular Economy
How far is your business in developing a clear business case (i.e. calculating the business benefits) for CE new initiatives?
How far is your business in establishing processes (e.g. take-back) and tools (e.g. circularity assessments) to support CE implementation?
How far is your business in taking risks and investing in Circular Economy initiatives?
To what extent has your business developed training programmes to enhance knowledge and skills regarding CE?
Strategy & Business Model Innovation
Readiness of 'Strategy & Business Model Innovation' measures the capabilities to enable a long-term strategy to be developed, which is linked to the development of new business models that can effectively deliver enhanced competitiveness and growth
To what extent is Circular Economy being embraced in your company's long-term strategy?
To what extent have company management committed themselves to Circular Economy initiatives and allocated resources?
To what extent has your business identified new potential value propositions across the product life cycle?
How far is yourbusiness in communicating the value of new offerings to the market?
How far is your business in defining new revenue streams and financial models (e.g. resell the product)?
Product & Service Innovation
Readiness of 'Product & Service Innovation' measures the capabilities necessary to develop new solutions (incl. products and services) that are suitable in a Circular Economy context
To what extent is your business developing and delivering Product/Service-Systems (e.g. additional services, subscriptions, sharing solutions)?
How far is your business in developing products and services considering extended lifetime (design for maintenance, modularity, etc)?
How far is your business in developing products and services considering End-of-Life (e.g. design for remanufacturing, recycling?
How far is your business in developing products and services that can be shared with other users (e.g. car/bike sharing)?
Manufacturing & Value Chain
Readiness of 'Manufacturing & Value Chain' measures the capabilities that will help you to create new value chain engagements and partnerships, aimed at maximum value creation from finite resources
To what extent has your business established new partnerships in the value chain to enable a circular business?
To what extent is your business collaborating with and/or influencing suppliers to encourage circular initiatives?
To what extent is your business using recycled/renewable/biodegradable materials in manufacturing processes?
How far is your value chain and manufacturing in entering industrial symbiosis (e.g. using waste streams as raw material)?
Technology & Data
Readiness of 'Technology & Data' measures your capabilities for the creation of value, through enhanced data management and sharing of the provided solutions
How far is your business in applying technology for product monitoring during the use phase (e.g. sensors, Internet of Things)?
How far is your business in applying technology to support the products for extended lifetime (e.g. spare parts, easy repair, upgradability)?
Use, Support & Maintenance
Readiness of 'Use, Support & Maintenance' measures the capabilities need to provide enhanced maintenance and repair services, aiming at an extended value creation from the provided solutions
How far is yourbusiness in supporting and servicing the product during the use phase (e.g. maintenance, advice)?
How far is your business in repairing products so to extend their lifetime?
How far is your business in establishing sharing platforms which can encourage shared product use and access?
Takeback & End-of-Life Strategies
Readiness of 'Takeback and End-of-Life Strategies' measures the capabilities that will ensure maximised value of end-of-life products
How far is your business in establishing takeback systems for products after their use (i.e. reverse logistics)?
How far is your business in disassembling and remanufacturing products, so they can be sold to other customers?
How far is your business in recovering the value out of products at End-of-Life (e.g. through material recovery)?
Policy & Market
Readiness of 'Policy & Market' measures the external readiness of the legislative frameworks and markets for the development and provision of circular solutions
How far is your business in influencing the market readiness for 2nd-life products (e.g. remanufactured or recycled products)?
How far is your business in influencing the market readiness for new business models (e.g. leasing instead of selling)?
How far is your business in co-developing new circular solutions with key value chain stakeholders (e.g. recyclers, service providers, logistic)?
How far is your business in influencing the sectorial legislative frameworks related to the implementation of CE initiatives?
How far is your business in influencing the national and international legislative framework related to the CE implementation?

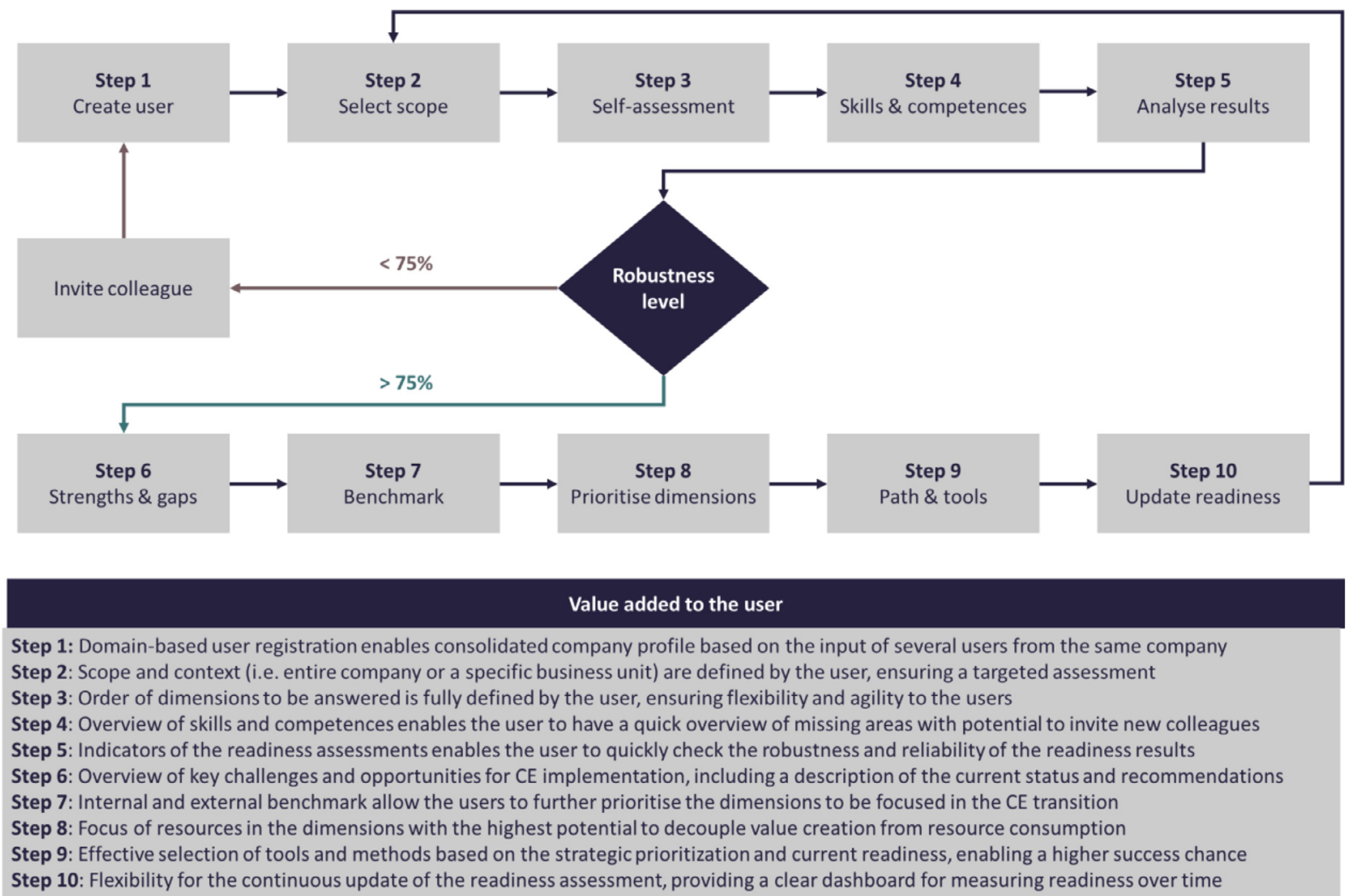

Fig. 3. Step-by-step approach for the use of the MATChE CE self-assessment tool, with an indication of the value added to the user in each step.

sessment (see also the examples in Fig. 4). 'Total readiness score' is a count of the aggregated readiness score of 150, considering that there are 30 aspects (questions) with a maximum possible score of '5' per aspect. The total score is, in itself, not entirely comparable, from business unit to business unit, but it nevertheless gives an indication of how far on the path that particular company/business unit is. 'Assessments' provides a count of the amount of assessments carried out for a particular company or business unit (i.e. number of different users submitting an assessment). 'Agreement' is a measure (low-medium-high) of the agreement level of the responses to the assessment for the particular company/business unit, calculated by measuring the standard deviation between them. 'Skill coverage' shows the level of coverage of the nine above-mentioned expertise areas. Finally, 'Robustness' is a measure of how much the user can trust the results on a given readiness assessment, which is the product of the number of assessments, standard deviation between the assessments and skill coverage.

If the robustness is low (calculated based on the number of assessments, agreement level and skills coverage), the user is encouraged to invite other colleagues from different functions to enhance the robustness of the results – an indication of missing skills is provided by the MATChE tool. Enabled by the allocation and domain-based company registration, the MATChE tool allows any user to invite a colleague within the same email domain, borrowing a principle from 'viral sharing' (Hoffman et al., 2020) to encourage as many colleagues as possible from the same company to contribute to the readiness assessment and thus building as true-to-reality a picture as possible, of the current readiness of the company to transition to CE. The more trustworthy the data within the tool, the more value it has. One important way to ensure trustworthiness of the data is to ensure multiple data entries per entity (company) registered on the platform. Therefore, the tool is encouraged to be used by as many colleagues as possible, within each participating company.

When the robustness is high, Step 6 involves the identification of strengths and improvement opportunities, based on an overview of the eight CE dimensions. Depending on the resulting consolidated CE readiness score for a given company and its business units, a summary is provided, aspect-by-aspect, dimension-by-dimension, of the current readiness, plus context-specific recommendations about how to increase the readiness for a particular CE aspect. Furthermore, an auto-generated PDF report can be created, summarising the particular business unit or company view, regarding current readiness and improvement recommendations.

Step 7 enables companies to benchmark the results internally (i.e. across different business units) and/or externally (e.g. companies from the same size, sector, region or business type). After having completed at least one readiness assessment, a user is able to carry out an internal benchmark between other business units and the company level within the company. The tool provides a list of comparative strengths and gaps and creates a report for the user to download. In addition, it is possible to carry out an external benchmark with all other companies on the MATChE tool. Furthermore, four filters make it possible for the user to benchmark external companies according to: primary sector; company type (B2B,

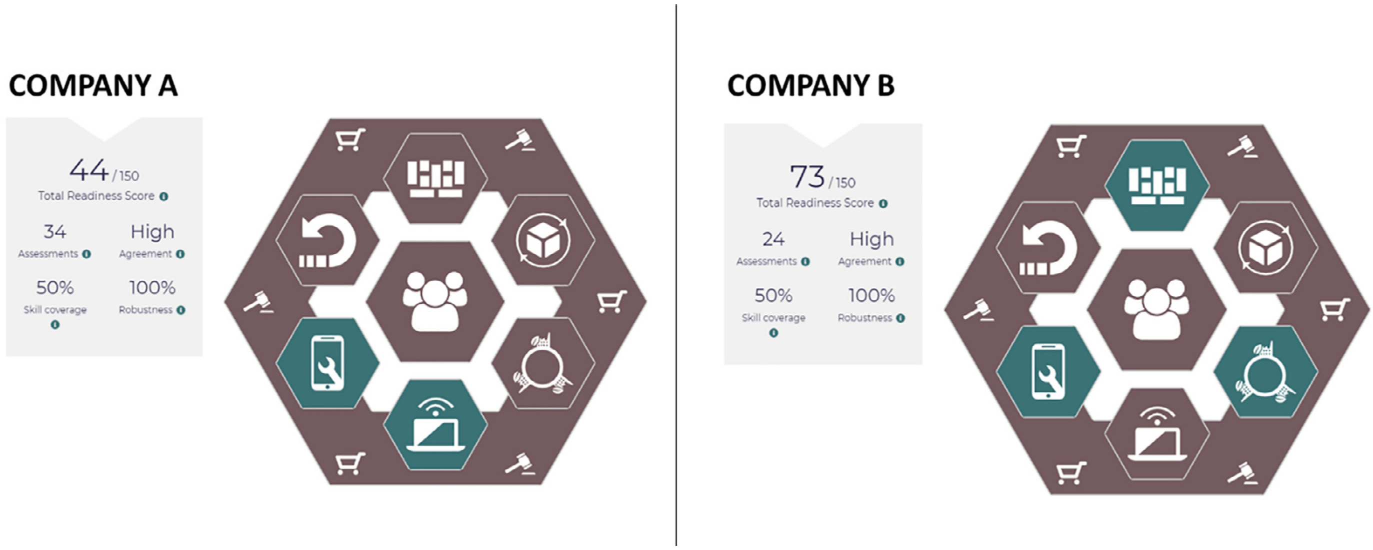

Fig. 4. CE readiness profile of companies A and B, with an overview of the readiness indicators and an indication of key strengths (represented in green) and improvement opportunities (represented in grey).

B2C, B2G); country; and company size. These filters *only* function if they capture a minimum of five external companies with the same characteristics as the filter, in order to preserve the anonymity of the data.

The prioritisation of the key CE dimensions for enhanced readiness based on their importance (low, medium and high) and timeframe (now, near and far) is performed in Step 8. A prioritisation of eight CE dimensions is possible to make, through a feature of the MATChE tool, in terms of 'importance' versus time to implement. By prioritising the dimensions to work with, a so-called 'transition path' can be charted, with recommendations for a transition process. Step 8 is followed by the selection of the implementation path and the best tools to support readiness enhancement, on the basis of current readiness and on the prioritised CE readiness dimensions (Step 9). The MATChE tool is equipped with a number of CE methods and tools (101 at the time of writing). These tools are categorised, with respect to their fit to: readiness dimensions; readiness levels; transition path status; organisational level the tool is suitable for (strategic, tactical, operational); and whether the tool is targeted at single users or teams. In addition, the tools are made available for download by the user. Depending on the readiness status of the user's company or business unit, the tools are 'promoted' as suggestions, to aid the transition process.

The readiness can be re-evaluated at a frequent basis, to support the identification of new improvement opportunities for the implementation of new CE initiatives (Step 10). It is possible for the user to go in at any time and perform an update of the data for a readiness assessment. The idea of this feature is to allow updated readiness assessments, after an improvement action, pilot project, competency lift, or similar has been carried out within the company and/or business unit in question. It also allows for the documentation of the evolution of the companyś CE readiness over time, which can be used for internal and external communication.

The final noteworthy feature of the CE readiness assessment tool – and in many ways, perhaps the most fundamental – is data security. The project responsible for creating the MATChE tool is under the strictest of regulations within its university, regarding data security, both with regards to GDPR and in terms of good data management practice. Expired or abandoned user data and company are purged on a regular basis. The MATChE tool is resident on a dedicated and encrypted secure server, with no other shared users. And with respect to the integrity of user logins, generic email domains (such as @gmail.com, @hotmail.com) are excluded from being able to register on the platform, as are known spoof mail domains (a blacklist is maintained). This measure ensures that the data on the tool are both kept safe from unwelcomed and unauthorised users, as well as kept as 'clean' as possible, to allow for optimal benchmarking and analytics.

4.2. User status and exemplary demonstration

The MATChE tool is, at the time of writing, supporting over 330 manufacturing companies (incl. 900+ users), spread across 16 manufacturing sectors and 38 countries. The key professional/job functions represented in the tool are: (i) Sustainability; (ii) Research & Development; (iii) Product Design and Development; and (iv) Strategic Planning. B2B and B2C companies are well represented, but B2G companies are less so.

To exemplify the use of the MATChE tool in a real-life context, the CE readiness of two companies from different sectors are described in this section. Company A is a large global manufacturing company, providing consumer electronic devices (i.e. B2C), with headquarters in Europe. Company A has defined Circular Economy as part of their overall sustainability strategy, and wanted to explore how to enhance the circularity of their business. In total, 34 different employees from the company engaged in the CE readiness self-assessment (steps 1-5), which was focused on the entire company as a whole (i.e. no specific business units were selected) (step 3). Company B is a global manufacturing company providing wood products in a B2B context, with headquarters in North America. Company B has been working with sustainability for many years, and engaged in the development of Circular Economy initiatives in order to explore new business opportunities for decoupling value creation from resource consumption. In total, 24 employees from Company B engaged in the CE readiness assessment, which focused on one specific business unit, which had the higher potential for new circular business models.

The consolidated readiness results for both companies (step 6) are presented in Fig. 4, with an overview of the key readiness indicators and an indication of strengths and improvement opportunities. Despite having a skill coverage of 50%, both companies managed to have a high amount of assessments (34 and 24, respectively) and a high agreement level (i.e. low standard deviation), which resulted in a high robustness of the results.

The total readiness score of Company A is 44 (out of 150), with key strengths in two dimensions: ´Technology & Data´ and ´Use, Support & Maintenance´. Company A is planning scale-up of products monitoring during use and repair services, and has already full implementation of service support provision systems. The key improvement opportunities within the other six dimensions are related to:

- Organisation: calculating the business case for CE and structuring the right process and tools.
- Strategy & Business Model: developing a long-term strategy for CE and communicating the overall value proposition to customer.
- Product & Service Innovation: developing product/service-systems, with products designed for end-of-life and sharing schemes.
- Manufacturing & Value chain: establishing new partnerships to enable circular solutions and identifying opportunities for industrial symbiosis.
- Takeback & End-of-Life Strategies: designing takeback systems, remanufacturing products and recycling materials.
- Policy & Market: exploring the market for second hand products and influencing legislation towards higher circularity within the electronic sector.

Company B has a total readiness score of 73 (out of 150). ´Strategy & Business Model´, ´Manufacturing & Value Chain´, and ´Use, Support & Maintenance´ are the key strengths of Company B in terms of strengths. The company is actively implementing circularity in their key business strategy, and is piloting a number of new circular business models to explore their market potential. Furthermore, the company is active in the establishment of new partnerships across the value chain, which are also focused on the investigation of materials with a higher circularity. Company B is also scaling-up service support platforms and repair services to extend the product life.

The key improvement opportunities within the other five dimensions are related to:

- Organisation: being able to take risks and invest for the implementation of new concepts and initiatives.
- Product & Service Innovation: designing for life extension and designing sharing systems.
- Technology & Data: exploring new technologies to allow extended product use.
- Takeback & End-of-Life Strategies: remanufacturing products and recycling materials.
- Policy & Market: exploring the market for second hand products.

On the basis of the readiness profile, Companies A and B performed an external benchmarking (step 7), which supported the prioritisation of the dimensions to focus (step 8). While Company A decided to focus on ´Strategy & Business Model´ and ´Product & Service Innovation´ (two of the identified improvement opportunities), Company B decided to continue focusing on their strengths (e.g. ´Strategy & Business Model´) in addition to selecting two additional improvement areas (i.e. ´Organisation´ and ´Product & Service Innovation´ dimensions). At the time of writing, both companies are implementing a number of initiatives within the selected dimensions, supported by a number of tools proposed from the MATChE tool and complemented with other tools that are connected to their key business processes (step 9). Once finalised, it is expected that the companies will perform a new readiness assessment (step 10), to be able to measure the readiness enhancement and to plan the next steps in their journey towards Circular Economy.

5. Discussion

The successful implementation of circular initiatives demands a thorough understanding of the company´s readiness profile (incl. a deep understanding of key strengths and gaps) and a tailored approach for the development of transition paths for CE implementation, which respects and builds upon the identified existing readiness. Hence, understanding how CE readiness and CE implementation relate to each other increases the probability of successful CE implementation and is essential to leverage CE potential towards sustainable growth.

The application of the MATChE readiness tool with the identification of strengths and improvement opportunities for CE, as well as the internal and external benchmarking, increase the degree to which the involved employees perceived the urgency for the transition to CE which is one of the key success factors for the CE transition. In addition, the application of the MATChE tool supports a higher alignment within the organisation in relation to on-going initiatives and the priorities for CE implementation. Combined with the extensive database of methods and tools, which are pre-selected according to the current readiness and prioritised areas, the tool enables the development of a feasible transition path which can enhance the success rate of CE initiatives, and ensure the evolution from pilot projects to scale-up and full implementation.

Given the amount and granularity of data that the tool is able to collect and analyse, the MATChE CE readiness self-assessment tool has been designed so as to provide valuable research insights into the readiness of the industry with respect to CE transition. These insights can be created on the basis of many different dimensions, which are of potential use to not only the companies that the tool's main interface is designed for, but also researchers, policy-makers and strategic funding agencies. In this context, there is a potential of using the MATChE tool to continuously provide a dashboard with anonymised data of CE readiness in different sectors, regions, company sizes and types to support further research and policy-making within CE implementation.

In addition to the practical contribution to the manufacturing industry, the MATChE tool also contributes to the state-of-the-art in the CE literature, enabling the understanding of the key dimensions and aspects to evaluate CE readiness at an organisational level. MATChE complements existing similar CE readiness tools with different analysis levels: country level (Momete, 2020; Garcia and Cayzer, 2019); sectorial level (Siew, 2019); ecosystem level (Parida et al., 2019); regional level (Pigosso et al., 2018); and individual employee level (Singh et al., 2018), as described in Section 2, Literature review. In relation to the scope (i.e. circularity evaluation at the company level), the most similar approach to the MATChE tool is Circulytics®, launched by the Ellen MacArthur Foundation in 2019. Despite not being developed to evaluate the CE readiness and not having been published in academic literature, the Circulytics® tool (Ellen MacArthur Foundation, 2020) presents a number of similarities to the MATChE platform, which are worth discussing. The key characteristics of the MATChE CE readiness self-assessment tool and its comparison to Circulytics® are summarised in Table 2.

Despite the similarities between MATChE and Circulytics® in contributing with the overall understanding of CE implementation at a company context, each tool has different overall goals and approaches. In future studies, it might be interesting to explore the potential synergies of both approaches, to enable companies in their CE transition, when applied in a combined fashion. It would furthermore be interesting to compare the results of companies that have engaged in both initiatives to understand whether there is a correlation between the CE readiness score (MATChE) and the CE circularity index (Circulytics®).

Table 2
Comparative tool of the MATChE platform and the Circulytics® tool (* corresponds to estimations by the authors).

Characteristic	MATChE	CIRCULYTICS®
Main goal	Measure and enhance readiness for CE transition, based on a customised transition path	Measure the circularity level of companies
Score calculation	30 aspects, divided across 8 dimensions	18 indicators, divided across 11 themes
CE dimensions measured	Organisation; Strategy & Business Model; Product & Service Innovation; Manufacturing & Value Chain; Technology & Data; Use, Support & Maintenance; Takeback & End-of-life; Policy & Market	Strategy and planning; People and skills; Innovation; Operations; External engagement; Product & Materials; Services; Assets; Water; Energy; Finance
Data input	Qualitative	Mix of qualitative, semi-quantitative and quantitative data
Level of depth	High-level	High-level
Scope	Company level Business unit level	Company level only
No. of users involved in assessment	Min. 1, max. ∞ In-built consolidation feature of readiness profile	One representative per company
Reliability of results	Robustness function, calculated based on the agreement level (standard deviation), skill coverage and number of assessments	Reliability is solely based on the input/output data from the user, and not evaluated within the tool
Advice after completing	Readiness dashboard Full report with current status and recommendations CE transition paths, based on 99+ tools and supporting cases	Scorecard Communications toolkit
Benchmarking possibilities	Internal benchmarking External benchmarking	Indirectly, through annual data insights
Availability	Online, 24/7	Registration-based, based on a 3rd part software
Time to complete	Circa 1 hour per person for the self-assessment, can be completed as a workshop	Data collection: weeks-months* Questionnaire: 2-3 hours*

6. Conclusions

The MATChE tool was developed based on the identification of the eight key dimensions that are necessary for manufacturing companies in making the transition to CE: (1) Organisation; (2) Strategy and Business Model Innovation; (3) Product & Service Innovation; (4) Manufacturing & Value Chain; (5) Technology & Data; (6) Use, Support & Maintenance; (7) Takeback & End-of-Life Strategies; and (8) Policy & Market. In total, 30 aspects were identified to support the identification of the companies´readiness in each one of these dimensions, which are used for a self-assessment by manufacturing companies. By analysing a number of contextual factors (e.g. organisational culture; policies and procedures; past experience; organisational resources and organisational structure), the CE readiness self-assessment tool provides important guidance to support the successful transition towards of manufacturing companies in a CE, which has the potential to support minimising the currently observed circularity gap. The CE readiness profile enhances the understanding of strengths and gaps for CE implementation within an organisation, based on a cross-functional effort within a company. In addition to that, the MATChE tool also allows companies to perform internal and external benchmarking studies to support the prioritisation of key CE focus areas and dimensions; and to plan relevant transition paths with support of CE-related tools, methods and approaches.

At the same time, the MATChE tool has clear limitations. Firstly, the scope of the tool is currently limited to manufacturing companies. This delimitation was chosen in order to be fully applicable to the main focus group for the research and to be as specifically useful as possible to this sector. Future directions from this initial scoping could go a level deeper and more specific (e.g. electronic equipment manufacturing, packaging manufacturing), or broadly to other sectors (e.g. maritime branch, agro-food sector, service industry). Such an expansion of the scoping for the tool (which the authors are currently planning), should be carried out with the intention of retaining as many of the current dimensions and aspects as possible, to preserve comparability, whilst obviously having to change some dimensions and aspects, to be more relevant for the new scope. The second limitation of the tool is that it provides a consensual starting point to measure readiness in a company, but does not attempt to provide any quantitative goals or targets, as such. This was, again, a conscious choice, when developing the MATChE tool, in order to retain focus on creating an initial baseline for companies to build on. One development, in the future, could be to build quantifiable indicators, to lead the change, also in relation to specific performance targets – but such an addition to the tool would clearly require more granularity of multiple scopes, within each sector. The third main limitation of the tool is that it does not consider material and energy flows as an indicator for the calculation of the CE readiness profile, nor for the prioritisation of the CE focus areas. While the understanding of the organisational readiness remains as the main goal of the tool, it might be relevant to support the prioritisation process of focus areas by combining the readiness profile (i.e. the results of the MATChE tool) with the circularity potential of different business units/CE dimensions, by using existing metrics for circularity assessment at company level (e.g. Circulytics®). In that case, the evaluation should be done based on quantitative data, which will most likely be provided by one representative from the company and/or business unit.

Finally, there has been an increased interest in the use of the CE readiness approach by other types of stakeholders than only manufacturing companies. Future research is ongoing for the expansion of the scope of the MATChE tool in a number of different directions (e.g. value chain, sectors, types of companies).

Declaration of Competing Interest

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

Acknowledgement

This article is one of the outcomes of the research project MATChE (Making the Transition to a Circular Economy), supported by the Danish Industry Fund (project number: 2016-0202). The project has been led by the Technical University of Denmark, supported by an advisory board, comprising the Confederation of Danish Industry, the Danish Environmental Protection Agency and Chora 2030. The authors would like to thank the MATChE team (Lærke Sofie Spaabæk Perrild, Louise Laumann Kjær, Nicklas Funk, and Mathias Bahrenscheer) for supporting the development of the tool, facilitating the engagement with companies and promoting relevant discussions about CE implementation. Special thanks go to the participating companies for the opportunity and collaboration that made this research possible.

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