COMMENTARY AND DISCUSSION ARTICLE

Life cycle assessment and circularity indicators

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Abstract

Purpose In a context where the transition to a circular economy is increasingly required, it is necessary to clarify the relationship between sustainability and circularity. In this commentary we summarise what are circularity indicators and what is LCA (Life Cycle Assessment), and we discuss their potential role in improving circular decision making.

Methods Based on literature, a focus on how circularity indicators and LCA could be used in circular decision making is presented. Moreover, an analysis of recent studies has been carried out to identify the relationship between LCA and circularity indicators.

Results and discussion We can state that no authors have concluded that circularity indicators can be used alone to choose the best option in circular economy projects. This is because the circularity indicators only provide a partial view on the environmental performance of a system. At the same time, it appears that the circularity indicators are easier to communicate, and a high degree of circularity could help to build good relationships with customers and increase reputation among stakeholders, as well as to have an easier access to funding.

Conclusions and recommendations At the end, we propose a procedure to include both the LCA and the circularity measurement in the assessment of circular economy strategies. While still at an early stage of conceptualisation, it gives an idea on how to integrate environmental sustainability aspects into circular economy initiatives.

Keywords Circular economy · LCA · Life cycle assessment · Sustainability · Circularity indicator · Assess circularity

1 Introduction

Circular economy (CE) is an approach developed due to the need to provide concrete response to implement the concept of sustainable development (Murray et al. 2017; Corona et al. 2019; Saidani et al. 2019) shifting from a linear economy model to a circular one (Ellen MacArthur Foundation 2013). Although CE is considered by different authors a relatively young approach (Murray et al. 2017; Sassanelli et al. 2019), this was first coined and used in 1990 (Pearce and Turner 1990). Currently, several definitions of

CE could be found in the literature, as observed by some authors (Geissdoerfer et al. 2017; Kirchherr et al. 2017). Such definitions derive from different fields (Korhonen et al. 2018). One of the most cited (Kirchherr et al. 2017, p. 229) describes CE as "an economic system that replaces the 'end-of-life' concept with reducing, alternatively reusing, recycling and recovering materials in production/distribution and consumption processes. It operates at the micro level (products, companies, consumers), meso level (eco-industrial parks) and macro level (city, region, nation and beyond), with the aim to accomplish sustainable development, thus simultaneously creating environmental quality, economic prosperity and social equity, to the benefit of current and future generations".

The diverse conceptualizations of CE (Kirchherr et al. 2017; Murray et al. 2017) lead to put into practice alternative circularity strategies (Corona et al. 2019). Hence, CE has been considered a sort of umbrella concept that summarized different approaches (Bracquené et al. 2020). For example, CE is often associated to the 3 or 4R approach—reduce, reuse, recycle and recover (Kirchherr et al. 2017; Murray

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et al. 2017; Helander et al. 2019)—or to business models circular-oriented. The variety of approaches and strategies depends on the absence of a standardized framework. To deal with this, a group of ISO Standards are currently under development by the Technical Committee ISO/TC 323, circular economy (ISO/TC 323 2021). This group of standards will include not only a set of principles and guidelines for the CE application, but also a measuring circularity framework. Indeed, measurement tools could be useful to improve systems (Sassanelli et al. 2019). To date, a variety of circularity indicators have been developed to tackle the lack of a harmonized methodology to assess CE strategies (Peña et al. 2021).

Albeit CE is oriented to achieve the overall sustainability, according to Helander et al. (2019), it is important to explore deeper how CE affects environmental sustainability for two main reasons: the risk of problem shifting and rebound effects which are directly linkable to environmental issues. Hence, each CE strategy should be carefully assessed because it not necessarily provides environmental benefits.

Life cycle assessment (LCA) methodology may be applied to identify the most promising circular economy strategies and options for improving the environmental performance of society's consumption and production patterns, as stated in the recent position paper by the Life Cycle Initiative (Peña et al. 2021). In Sect. 2, a focus on how circularity indicators and LCA could be used in circular decision making is presented.

2 Focus on circularity indicators and LCA

2.1 Circularity indicators and their potential role in circular decision making

Recognizing the need for a circular economy to decouple economic progress from resources depletion, the so-called circularity indicators have been developed, albeit in a disorganized way (Sassanelli et al. 2019). Research in the field of CE is currently evolving. Often, the metrics and indicators present contradiction in both form and content (Corona et al. 2019). Moreover, as CE is a multifaceted concept, its measurement generates different interpretations (Saidani et al. 2019). Therefore, several classifications of circularity indicators have been proposed (Elia et al. 2017; Corona et al. 2019; Sassanelli et al. 2019).

Circularity can be evaluated at different levels, i.e. at micro-, meso- or macro-level. So, circularity indicators can measure the circularity of a product or a system, i.e. the ability to conserve both the quantity and the quality of a material (Bracquené et al. 2020), or also how effective a company is in making the transition from linear to circular models. On the product level, indicators can be useful for designing new products, for internal reporting activities, or for setting procurement objectives. Instead, at company level, indicators can be used internally to compare different product ranges or to identify the progress of them. Circularity indicators can be also used externally to benchmark the circular level of more companies (Ellen MacArthur Foundation and Granta Design 2015). Indeed, by setting specific targets according to these indicators, the improvement of each company thanks to CE strategies could be monitored (Saidani et al. 2019). For the above reasons, circularity indicators offer a concrete contribute to the improvement of circular decision making. However, there are also limits in the application of such measurement tools. For example, the copious number of indicators and—in some cases—the ambiguity of their aim make difficult both the choice of which is more suitable in a specific context (Saidani et al. 2019) and a potential comparison.

The most used indicators are those referred to macro-level evaluation, generally based on material flow analysis (MFA) (Bracquené et al. 2020). Regarding the evaluations at micro-level, the material circularity indicator (MCI) developed by Ellen MacArthur Foundation and Granta Design (2015) seems to be the most appreciated (Bracquené et al. 2020). MCI gives an indication on how much the materials which constitute a product circulate; in particular, it is able to measure the level of linear and restorative flows. Moreover, it provides information about the utility of a product (Ellen MacArthur Foundation and Granta Design 2015). However, such indicator does not fully inform about the sustainability of the product.

2.2 LCA and its potential role in circular decision making

LCA is a methodology developed for assessing and quantifying the potential environmental impacts associated with entire product life cycles. It is standardized in the ISO 14040 series. As previously mentioned, the Life Cycle Initiative proposed such methodology for identifying the most promising circular economy strategies. In fact, LCA can be applied to build more consistent and robust CE strategies by considering potential upstream and downstream impacts and encompassing all relevant resources and impact categories. Moreover, LCA can provide a holistic perspective into decision making, which include also both economic and social sphere, if it applied in a comprehensive way (Peña et al. 2021).

However, the LCA methodology is not perfectly able to measure the degree of circularity of the system under

study. Two main reasons explain this limitation. First is the way LCA models raw materials and resource considerations, which often takes the linear economy as the frame of reference. LCA was in fact born to analyse the life cycle of a product *from cradle to grave*, i.e. from the acquisition of the raw materials to the disposal of the product after its use (Stanchev et al. 2020). Only later, rules to evaluate the impacts and benefits of reuse and recovery were developed, thus extending the study scope *from cradle to cradle*. However, some difficulties still exist, e.g. the lack of a consistent modelling of open recycling loops (Peña et al. 2021) as well as the lack of clear guidelines for accounting for multiple material uses with changing material qualities (Haupt and Zschokke 2017). Second, the most common characterization methods used in the LCA for the calculation of impact indicators related to the consumption of resources do not consider those in anthropogenic deposits as available (Sonderegger et al. 2020). A new approach, but still under development, is based on the concept of dissipation rather than consumption (EC-JRC 2020). Despite these limitations, the outcomes of the reviews of Corona et al. (2019) and Sassanelli et al. (2019) show that one of the most used methodology to assess CE is LCA. Corona et al. (2019) found that LCA is adopted to compare and to choose among different CE strategies. For the same authors, the holistic approach and the accumulated experience in end-of-life assessments are the main suitable characteristics of LCA in circularity measurement. LCA allows to understand and to evaluate whether the claimed

environmental benefits of CE solutions can be achieved and to what extent. This methodology permits to identify also the most critical aspects of a CE strategy which need to be improved (Peña et al. 2021). Another strong point of LCA is its aim, i.e. to avoid the burden shifting. Circularity metrics are not able to do the same, because they are focused only on few goals (Corona et al. 2019) or a single activity (Helander et al. 2019).

3 Relationship between LCA and circularity indicators

3.1 Conclusions of some recent studies

Haupt and Zschokke (2017) stated that it was demonstrated that the most circular solution is not necessarily the most environmentally preferable option. Some more recent papers, where the LCA and the assessment of the circularity are carried out separately, reached the same conclusion (Table 1). For example, Lonca et al. (2018), in their analysis on the tire industry, concluded that extending lifetime through retreading and introducing recycled material improves the MCI of a tire but does not necessarily improve impacts on human health and ecosystems. Pauer et al. (2019) in their study about food packaging defined some circularity indicators to inform about material flows at the product level and the use of renewable energy. They concluded that further studies are needed to estimate how the improvement of the pro-

Table 1 Some recent studies that include both LCA evaluation and circularity assessment

Reference	Application	Methodologies when applied separately
Bracquené et al. 2020	Washing machines	LCA, product circularity indicator (developed in the study) and MCI
Glocic et al. 2020	Alkaline batteries	LCA and MCI
Lonca et al. 2018	Tires	LCA and MCI (adapted)
Pauer et al. 2019	Food packaging	LCA and circularity indicators (input related: recycled content, reuse rate, renewable content; output related: recyclability, recycling rate, recycling output rate, downcycling factor, reuse rate, compostability; energy: share of renewable energy)
Schmidt et al. 2020	PET bottle waste management	LCA and six material efficiency measures including the circularity potential developed by Eriksen et al. (2018)
Stanchev et al. 2020	Anaerobic treatment of dairy processing effluents	LCA and two new circularity metrics based on material flow analysis and LCA (i.e. the Material circularity performance indicator based on the Demand Minimization Index—suggested by Agudelo-Vera et al. (2012)—and the Environmental circularity performance indicator based on the ratio of the total environmental benefits and costs)
Reference	Application	Methodologies when integrated
Mantalovas and Di Mino 2020	Asphalt mixtures	A composite indicator of environmental sustainability and circularity assessment where the environmental sustainability is quantified by LCA and circularity by MCI (adapted)
Niero and Kalbar 2019	Beer packaging	Two sets of indicators are coupled via a MCDA: (i) material circularity-based indicators, namely material reutilization score and MCI, and (ii) a selection of life cycle-based indicators relevant for beer, i.e. climate change, abiotic resource depletion, acidification, particulate matter and water consumption

posed circularity indicators really reduces the environmental impact over the life cycle of packaging. Bracquené et al. (2020) for a case study for washing machines calculated the LCA, the MCI and a product circularity indicator (PCI) developed in the study to overcome the main limitations identified for the MCI. The authors identified some potential trade-offs and concluded that it is important to stress that the PCI only measures the circularity of the flows whereas other effects on the environment, typically assessed with a LCA, are not covered. Trade-offs were also discussed in Glocic et al. (2020), e.g. those between increasing circularity and minimizing environmental burden.

Schmidt et al. (2020) are indeed of a different opinion. In their analysis of polyethylene terephthalate (PET) bottle waste management systems in three countries, they applied LCA together with the calculation of six material efficiency indicators aiming at different stages of the waste and recycling system. They stated that a comparison between the results of the material dimension and of the environmental dimension shows that the tendency of the results in those two dimensions is similar. Stanchev et al. (2020) introduced two metrics to evaluate respectively the material and environmental circularity performance of an anaerobic digestion treatment in the dairy sector. However, in the paper, no comparison of the results obtained in the different assessments was made.

Some studies have tried to overcome this situation (i.e. in most of the cases LCA and circularity indicators give contrasting results) by considering an integration between LCA and circularity indicators (Table 1). Mantalovas and Di Mino (2020) proposed a methodology for quantifying the combined environmental sustainability and circularity of asphalt mixtures that incorporate reclaimed asphalt. The authors stated that this methodology can be used as a tool to rank different alternatives of asphalt mixtures, in terms of their environmental sustainability and circularity. They also underlined that an essential aspect of this methodology is that both types of assessment—environmental sustainability and circularity—are following identical system boundaries. This is an important consideration that enables the incorporation of both assessments' outcomes into one single indicator. Niero and Kalbar (2019) coupled different types of indicators (circularity and life cycle–based) via multi-criteria decision analysis (MCDA). Beer packaging was used as case study. The stand-alone application of the applied indicators presented a conflict and hence no alternative could have been selected. This problem of univocally identifying the best performing alternative was solved by the implementation of the MCDA.

3.2 Discussion

We think it is interesting to understand why some authors feel the need to use circularity indicators and if these indicators could be preferable, for some aspects, to the LCA approach.

Pauer et al. (2019) reported that in the field of their study (food packaging), producers are required to make packaging more sustainable, as this is under growing public scrutiny and regarded as a source of waste and pollution. However, they underlined a lack of a detailed guidance on how to calculate key environmental product indicators for packaging. In this context, as circularity is an increasing political and legal requirement, they identified circularity indicators as highly relevant for their assessment. Corona et al. (2019) underlined that material circularity indicators are easier to apply and to communicate to the public and to stakeholders and that, for this reason, are playing an import role in increasing the public awareness about CE. Lonca et al. (2018) highlighted that the assessment scale is a critical aspect in the identification of the type of circularity to quantify. Based on this, circularity indicators are considered essential to drive the transition to circularity at a micro-scale, for example, at a product or company level. At this level, according to Glocic et al. (2020), indicators are developed to incorporate circular economy ideas of resource minimization and cycling in the product design and management. To this aim, MCI can especially support a circular design to preserve the targeted materials that constitute the product.

However, most of the studies of Sect. 3.1, which apply LCA and circularity indicators separately, concluded that the results are often contrasting. This is because the circularity indicators only provide a partial view on the environmental performance of a system. Circularity metrics may be masking a burden shift towards increased energy consumption or polluting emissions (Corona et al. 2019). If the final aim is the sustainability, this implies that the choice between different alternative solutions cannot be based only on the circularity of the systems analysed.

Due to the different results in the two dimensions (i.e. circularity and environmental impacts), some authors have tried to integrate LCA and circularity indicators. The integration approach proposed by Mantalovas and Di Mino (2020) is based on a mathematical formula that includes an LCA indicator and an adapted MCI. The resulting composite indicator is considered adequate when the type of circular approach is of a closed loop type, so limiting its application. The integration of LCA and circularity indicators proposed by Niero and Kalbar (2019) is achieved through MCDA,

coupled with a scenario-based decision making approach. In the conclusions, they suggested some improvements to the approach proposed in their study, regarding the type and number of indicators used in the analysis, the application of more than one MCDA method and the extension of the life cycle perspective to the economic and social dimension.

Either considering the results separately or integrating the circularity and environmental sustainability assessments, no authors have concluded that circularity indicators can be used alone to choose the best option in circular economy projects. The Ellen MacArthur Foundation and Granta Design (2015) itself, which developed the MCI, stated that, in the future, the MCI could be one of the parameters considered an output from an LCA or eco-design approach alongside those already typically used. At the same time, many authors expressed the need to find a common ground for practical use of environmental metrics in circularity assessment and this has been recalled by Peña et al. (2021). This request has been received through the establishment of the aforementioned ISO Technical Committee (ISO/TC 323 2021) aimed at developing guidelines and support tools for the implementation of circular economy strategies. In this context, a clear guidance could be given on how LCA and LCA-based methodologies can provide a consistent methodological basis for assessing the sustainability of CE solutions.

4 Conclusions and open issues

We can conclude that the circularity indicators, alone, are not able to assess the overall environmental performance of circular strategies. Consequently, a study based on circularity indicators must be completed by an LCA study to verify that the circularity of the system also leads to an improvement in environmental performance. Similarly, LCA studies of products or services that provide for innovations attributable to circular economy models (e.g. increase in recycled content, increase in recyclability, increase in recycling efficiency, lengthening of the use phase, increase in the possibilities of reuse of product or parts thereof) can be completed and enriched by evaluations on the circularity of the system.

However, a complete analysis—such as that offered by the combination/integration of an LCA study with the evaluation of circularity indicators—is undoubtedly complex; it requires specific skills from the side of the analyst and the use of important resources by those who request it. Furthermore, the interpretation and communication of the results could be not so straightforward. At the same time, the increase of environmental pressures and of their effects on communities and ecosystems determines the urgency to continue to improve production systems and consumption

patterns; to do this in an informed and effective way, the potential of the tools described above can be exploited.

It is therefore desirable to develop a method shared by the scientific community to integrate sustainability aspects into circular economy initiatives, defining guidelines for carrying out and interpreting the results of joined studies of LCA and circularity. To this aim, we propose here a possible procedure to tackle the problem on how to integrate environmental sustainability aspects into circular economy initiatives, although at an early stage of conceptualization and open to feedbacks from the scientific community. We suggest, when different strategies are under decision, to prefer a holistic assessment of these, starting from an LCA. Later, after the exclusion of those strategies resulting with the worst impacts, the circularity analysis could be performed in support to the decision maker. Indeed, circularity cannot be totally ignored since numerous recent policies and support schemes are based on it. Moreover, as already highlighted, circularity is easier to communicate. A high degree of circularity could help to build good relationships with customers and increase reputation among stakeholders (Veleva and Bodkin 2018), as well as to have an easier access to funding, thanks to dedicated programmes (Acsinte and Verbeek 2015). At the same time, by subordinating circularity indicators to LCA, trade-offs between sustainability and circularity could be dealt with, and an acceptable level of environmental performance achievement is guaranteed.

In our opinion, this solution is less complex than including circularity indicators into LCA methodology. The addition of new indicators to the latter would make the interpretation of the results even more difficult due to the high number of indicators already included. Moreover, while a highest value in an LCA generally means a worse environmental performance and vice versa, a highest value in a circularity metric suggests a preferable strategy. This may increase the probability of mistakes in the interpretation of the results and makes their communication more difficult. For the same reason, particular attention should be paid in the weighting step (if performed), to avoid the risk of reversing the real result. A standardized procedure should be defined to guarantee a scientific validity and transparency for this type of assessment.

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