



## Full length article

## Coupling material circularity indicators and life cycle based indicators: A proposal to advance the assessment of circular economy strategies at the product level

Monia Niero<sup>a,\*</sup>, Pradip P. Kalbar<sup>b,c</sup><sup>a</sup> Aalborg University, Department of Planning, Sustainable Design and Transition, A.C. Meyers Vænge 15, 2450, Copenhagen, Denmark<sup>b</sup> Centre for Urban Science and Engineering (CUSE), Indian Institute of Technology Bombay, Powai, Mumbai, 400 076, India<sup>c</sup> Interdisciplinary Programme (IDP) in Climate Studies, Indian Institute of Technology Bombay, Powai, Mumbai, 400 076, India

## ARTICLE INFO

## Keywords:

Multi criteria decision analysis  
Life cycle assessment  
Circular economy  
TOPSIS  
Packaging  
Circularity indicators

## ABSTRACT

The debate on the identification of the most suited metrics for circular economy (CE) is open, no consensus has been reached yet on what CE indicators at product level should measure, which creates a subjective methodological framework for assessing CE strategies. In this study, we demonstrate that by coupling different types of indicators via Multi Criteria Decision Analysis (MCDA) it is possible to deal with conflicting situations where the selection of the best alternative can be biased by the choice of the metric. We use a beer packaging case, by simulating a situation where a company is interested in comparing the performances of different packaging from a CE perspective. We consider eight different beer packaging alternatives in two geographical contexts (United Kingdom and India). Two sets of indicators are coupled via MCDA: i) material circularity based- indicators, namely Material Reutilization Score and Material Circularity Indicator, 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. The results obtained by the application of the TOPSIS (Technique for Order by Similarity to Ideal Solution) method show that the different sets of indicators can be integrated and conflicts among them can be resolved. Overall, the application of different weighting scenarios does not change the ranking of the alternatives, thus confirming that the results are stable. Therefore, our proposal of coupling material circularity indicators with LCA indicators via MCDA can advance the assessment of CE strategies at the product level.

## 1. Introduction

The scientific debate on circular economy (CE) conceptualization and implementation has recently intensified (Babbitt et al., 2018; Bocken et al., 2017). An agreement on what the CE concept exactly mean is still missing and many definitions have been proposed by scholars (e.g. Blomsma and Brennan, 2017; Geissdoerfer et al., 2017; Homrich et al., 2018; Kirchherr et al., 2017; Korhonen et al., 2018). From a standardization point of view, the British Standard Institute

released in May 2017 the BS 8001:2017 standard titled “*Framework for implementing the principles of the circular economy in organizations - Guide*”. This is the first standard that aims to provide guidelines to organizations in the transition towards a more circular and sustainable mode of operation by drawing on the experiences and lessons learned from a range of organizations already involved with CE implementation. According to BS 8001:20,017 CE is “*an economy that is restorative and regenerative by design, and which aims to keep products, components and materials at their highest utility and value at all times, distinguishing*

**Abbreviation List:** A1, alternative 1; A2, alternative 2; A3, alternative 3; A4, alternative 4; AC, acidification; ALC, aluminium can; ARD, abiotic resource depletion; BS, British Standard; C2C, Cradle to Cradle® design framework; CC, climate change; CE, circular economy; CEIP, circular economy indicator prototype; CET, circular economy toolkit; EMF, Ellen MacArthur Foundation; EoL, end-of-life; FMCG, fast moving consumer goods; ILCD, international reference life cycle-data system; IN, India; IR, intrinsic recyclability; LCA, life cycle assessment; LCIA, life cycle impact assessment; MCDA, multi-criteria decision analysis; MCI, material circularity indicator; MFCA, material flow cost accounting; MRS, material reutilization score; NIS, negative ideal solution; OWGB, one-way glass bottle; PEF, product environmental footprint; PEFCR, product environmental footprint category rules (PEFCR); PIS, positive ideal solution; PM, particulate matter; RC, recycled content; RCR, recycling collection rate; ReR, reuse rate; RGB, refillable glass bottle; S1, scenario n.1; S2, scenario n.2; S3, scenario n.3; S4, scenario n.4; S5, scenario n.5; SK, steel keg; TOPSIS, technique for order by similarity to ideal solution; UK, United Kingdom; WC, water consumption

\* Corresponding author.

E-mail address: [monian@plan.aau.dk](mailto:monian@plan.aau.dk) (M. Niero).<https://doi.org/10.1016/j.resconrec.2018.10.002>

Received 12 July 2018; Received in revised form 30 September 2018; Accepted 1 October 2018

Available online 10 October 2018

0921-3449/ © 2018 Elsevier B.V. All rights reserved.

between technical and biological cycles” (British Standard, 2018). Such definition is highly inspired by the Ellen Mac Arthur Foundation (EMF) formulations of the concept (EMF and Granta Design, 2015; EMF, 2015, 2013), with an emphasis on the distinction between the two cycles (biological and technical), which is derived by the Cradle to Cradle® (C2C) design framework (Braungart and Engelfried, 1992). As outlined in the monitoring framework for a circular economy “*The transition to a circular economy is a tremendous opportunity to transform our economy and make it more sustainable, contribute to climate goals and the preservation of the world’s resources, create local jobs and generate competitive advantages for Europe in a world that is undergoing profound changes*” (European Commission, 2018). Therefore, there is a huge potential for contributing to the achievement of the Greenhouse Gases (GHG) emission reduction targets defined by the Paris Agreement (United Nations, 2015) by implementing the CE concept and monitoring its progress. The guidance provided by BS 8001:2017 is useful on the conceptual level through the identification of CE principles and strategies, but it is lacking on the operational and implementation level (Niero and Schmidt-Rivera, 2018; Pauliuk, 2018). According to BS 8001:2017 standard, the responsibility of choosing the appropriate CE performance indicators is borne by the organization implementing CE (Pauliuk, 2018). The debate on the identification of the most suited metrics for CE is very much open, no consensus has been reached yet which creates a subjective methodological framework for assessing CE.

Most of the available indicators measuring CE strategies refer to the macro (i.e. region, nation, sector) and meso levels (i.e. eco-industrial parks) and not to the product level scale (Linder et al., 2017). There are contrasting opinions among scholars on what CE indicators at product level should measure and whether indicators addressing single or multiple issues are more suited. Linder et al. (2017) recommend that a circularity metric at the product level should focus exclusively on measuring circularity, i.e. the fraction of a product that comes from used products, as a single attribute of product quality and not on environmental performance or competitiveness. Pauliuk (2018) provides, instead, a dashboard of new and established indicators for the quantitative assessment of CE for product systems and organizations. Such list addresses different categories of indicators, measuring both physical circularity, monetary value, and potential environmental impacts, mostly based on material flow analysis (MFA), material flow cost accounting (MFCA) and life cycle assessment (LCA). Saidani et al. (2017) criticized the ability of three existing approaches, i.e. Material Circularity Indicator (MCI) (EMF and Granta Design, 2015), Circular Economy Toolkit (CET) (Evans and Bocken, 2013) and Circular Economy Indicator Prototype (CEIP) (Griffiths and Cayzer, 2016), to measure product circularity performance both in terms of their applicability in industry and their accordance with CE principles. However, they also acknowledged that different indicators serve different purposes and some tools could be better in one situation, such as comparing rapidly the impact of two different materials on circularity performance, e.g., the MCI (EMF and Granta Design, 2015), meanwhile others are more product-centric and lifecycle thinking oriented. The relevance of using indicators based on life cycle thinking, such as carbon footprint, to complement material efficiency-based indicators has been demonstrated in the case of aluminium cans (Niero and Hauschild, 2017a), tidal energy device (Walker et al., 2018) and tyres end-of-life management (Lonca et al., 2018). LCA is based on the eco-efficiency concept, which focus on the optimisation of individual product systems, leading not only to a reduction in resource consumption and pollution, but also to the potential risk of optimizing inherently unsustainable systems, such as waste incineration in Denmark (Bjørn and Hauschild, 2013). Hence, an overall assessment of the environmental sustainability of product system needs coupling of indicators addressing complementary aspects, such as material circularity and performance from eco-efficiency (e.g. LCA indicators). The Multi-Criteria Decision Analysis (MCDA) framework can fit the purpose of addressing the multiple dimensions of circularity indicators and its use

has therefore been advocated (Niero and Hauschild, 2017b; Seager and Linkov, 2008). The MCDA comprise a set of methods based on various mathematical principles used to resolve conflicting objectives (Halog and Manik, 2011). It has been widely applied in various disciplines for decision making, e.g. to select the most sustainable stormwater management alternative in developing countries (Gogate et al., 2017), to determine a set of good alternative(s) for concrete production, considering environmental and economic criteria (Suárez Silgado et al., 2018) or for alternative screening and ranking in the waste management sector (Pires et al., 2011).

To the best of our knowledge, no previous study has coupled different indicators to measure the CE performances at any level (macro, meso or micro) via MCDA. At the product (i.e. micro) level the use of different types of indicators to assess CE performances has been tested in only a limited set of sectors, such as energy (Saidani et al., 2017), manufacturing (Walker et al., 2018) and packaging (Niero and Hauschild, 2017a), but only one type of product per time has been included in the analysis. Moreover, a lack of references to sustainability performance indicators or assessment methodologies with regard to CE activities was found in the analysis of corporate sustainability reports in the Fast Moving Consumer Goods (FMCG) performed by Stewart and Niero (2018). Only a limited number of companies present a dedicated set of key performance indicators for their CE approach, based on either metrics addressing material efficiency, LCA results or use of the C2C certification program. The present study focuses on the packaging sector, i.e. a sector with high priority for CE implementation (EC, 2015a; EMF, 2013). We contribute to advancing the assessment of CE strategies by simulating a situation where a company is interested in comparing the performances of different packaging from a CE perspective. The novel approach of coupling different circularity indicators with LCA based indicators by means of MCDA is proposed, which enables capturing the performance of the product system from both CE and eco-efficiency perspectives.

## 2. Materials and methods

We present an illustrative case where different material circularity indicators (Section 2.1) and life cycle based indicators (Section 2.2) are coupled via MCDA (as described in Section 2.3) in a case study including different beer packaging alternatives in two geographical contexts (Section 2.4).

### 2.1. Material circularity based-indicators

In the selection of the material circularity indicators addressing the product level assessment, we prioritized two indicators that are aimed to be used within a company context (Linder et al., 2017), developed by two of the most influential actors in framing and spreading the CE concept among businesses, i.e. proponents of the C2C design framework and the EMF. The selected indicators are the Material Reutilization Score (MRS) and the above-mentioned MCI.

The MRS is the metric used to quantify material reutilization, i.e. the criterion included in the C2C certification program addressing the recycling value of the materials (Cradle to Cradle Products Innovation Institute, 2016). With regard to the technical cycle, the MRS quantifies the recyclability potential of a product considering two variables: the intrinsic recyclability (IR) of the product, i.e. the % of the product that can be recycled at least once after its initial use stage and the % recycled content (RC). The MRS is given by the weighted average of the two variables, where the first one is given twice the weight of the second one, as reported in Eq. 1, with a final value ranging from 0 to 100.

$$\text{MRS} = [(\% \text{ IR of the product}) \cdot 2] + [(\% \text{ RC in the product}) \cdot 1] / 3 \cdot 100 \quad (1)$$

The MCI is the main index developed by the EMF and Granta in the context of the MCI Project aiming to find indicators to measure how well a product performs in the CE context (EMF and Granta Design, 2015). It provides an indication of how much a product's materials circulate, ranging from 0 to 1, in order to allow companies to understand *how far they are on the transition from 'linear' to 'circular'* (EMF and Granta Design, 2015). The MCI is essentially constructed from a combination of three product characteristics: the mass of virgin raw material used in manufacture, the mass of unrecoverable waste that is attributed to the product, and a utility factor that accounts for the length and intensity of the product's use. The parameters used to calculate the MCI refer to: i) destination after use, distinguishing among the percentages of recycling collection rate (RCR) and reuse rate (ReR); ii) percentage of recycled feedstock (RC); iii) efficiency of the recycling process, i.e. the yield during recycling, and iv) utility during use stage, i.e. use intensity with regard to an average product in the market. The MCI Dynamic Modelling tool provided by Granta has been used to perform the calculation of MCI (<https://www.ellenmacarthurfoundation.org/programmes/insight/circularity-indicators>).

## 2.2. Life cycle based- indicators

By life cycle based-indicators we refer to the life cycle impact categories indicators that are obtained from LCA. The selection of the most relevant impact categories to include in an LCA has been highly debated in the scientific literature, including its dependency on the sector of study (Kalbar et al., 2018, 2017a; Steinmann et al., 2016; Van Hoof et al., 2013). Product Environmental Footprint Category Rules (PEFCR) in the context of the PEF pilots initiative aims to ensure that LCA is carried out focusing on significant contributors (foreground and background processes) in life cycle stages, and relevant impact categories for the sector (Galatola and Pant, 2014). Therefore, we decided to select one product category for which PEFCR are available and for which packaging represents a contributing life cycle stage. We selected beer, where the influence of different packaging types is known to be relevant in terms of environmental performances (Amienyo and Azapagic, 2016; Cimini and Moresi, 2016). Thus, for the selection of the life cycle-based indicators, we focused on the most relevant impact categories listed in the final version of the PEFCR of beer (The Brewers of Europe, 2018), i.e. climate change, particulate matter, acidification, resource use (mineral and metals; fossil) and water use. Packaging and material production represent indeed (one of) the most relevant life cycle stage contributing to the impacts for climate change, respiratory inorganics, acidification terrestrial and freshwater, water scarcity, and resource use (both energy carrier and minerals and metals) (see Table 9 in The Brewers of Europe, 2018). The calculation of the life cycle-based indicators has been performed by means of the Instant LCA Packaging™ version 1.15.2 provided by RDC Environment, i.e. a customized software used by industry for packaging LCA, which has already been used to perform LCA on beverage packaging (Niero et al., 2016). The functional unit considered by the software is the containment and packing of 1 hectolitre (hl) of beer. System boundaries of this LCA was limited to the production of primary packaging, to take into account only the materials and align the calculations with the material circularity

indicators, thus excluding also the transport between different stage of life cycle (producer, consumer, recycler). The Life Cycle Impact Assessment (LCIA) methodology implemented in the software used refer to the International Reference Life Cycle-Data System (ILCD) recommended method (Hauschild et al., 2013), including the following impact categories: climate change (CC, kg CO<sub>2</sub>e<sub>q</sub>), abiotic resource depletion (ARD, kg Sb<sub>eq</sub>), acidification (AC, mol H<sub>eq</sub><sup>+</sup>), particulate matter (PM, kg PM<sub>2.5eq</sub>), water consumption (WC, m<sup>3</sup>).

## 2.3. Multi Criteria Decision Analysis and weighting sets

MCDA is most commonly used for addressing multiple conflicting objectives. Many methods can be used for MCDA: Greco et al. (2016) provides a review of the available methods. The use of compensatory and non-compensatory approach makes the major difference in the MCDA methods. In compensatory approaches the trade-off between the indicators is allowed, whereas non-compensatory approaches are usually based on outranking principles which use pairwise comparison of alternatives (Seppälä et al., 2001). Guitouni and Martel (1998) provides detailed guidelines for choosing the appropriate MCDA method for the particular decision problem. Based on these guidelines and analysis of similar decision contexts (Behzadian et al., 2012; Pires et al., 2011; Sohn et al., 2017), we have found that the TOPSIS (Technique for Order by Similarity to Ideal Solution) method is best suited for the problem being addressed in this work. The TOPSIS method uses Euclidian distance measure for identifying the alternative from the Positive Ideal Solution (PIS) and Negative Ideal Solution (NIS). PIS is basically a hypothetical alternative formulated using the highest score of the indicators in case of benefit type indicators (i.e. material circularity indicators) and lowest score of the indicators in case of cost type indicators (i.e. LCA indicators). Similarly, NIS is also a hypothetical alternative formulated using opposite logic that of PIS. In TOPSIS the alternative which is nearer to the PIS (i.e. resembles characteristic of PIS) and farther from the NIS receives the highest score (calculated using Euclidian distance measure). A detailed methodology of TOPSIS specific to processing of LCA indicators can be found in Kalbar et al. (2017b).

In MCDA indicator weights significantly influences the final ranks of the alternative and hence Kalbar et al. (2012) proposed a scenario-based decision making approach to properly structure the decision making problem. The scenarios describe the stakeholder's perspectives in terms of weights and final rankings can be obtained for the each of the scenario, which reflect the stakeholders' preferences more correctly. Considering this, we have defined five scenarios (S1-S5) representing the varying weights to each type of indicator representing various stakeholders' preferences (see Table 1). For example, in Scenario 1 (S1) equal weightage is given to all the indicators, whereas in Scenario 2 (S2) higher weightage is given to material circularity indicators. These weighting schemes are used to rank the various alternatives of the case study described in the next section.

## 2.4. Case study: beer packaging

We considered 8 packaging alternatives for beer in two geographical contexts, the United Kingdom (UK) and India (IN), addressing

**Table 1**  
Overview of the five scenarios (S1-S5) considered and associated weights assigned to each indicator.

Scenario n.	Material Reutilization Score (MRS)	Material Circularity Indicator (MCI)	Climate Change (CC)	Abiotic Resource Depletion (ARD)	Acidification (AC)	Particulate Matter (PM)	Water Consumption (WC)
S1	0.143	0.143	0.143	0.143	0.143	0.143	0.143
S2	0.200	0.200	0.150	0.150	0.100	0.100	0.100
S3	0.100	0.100	0.150	0.150	0.200	0.200	0.100
S4	0.100	0.100	0.200	0.200	0.150	0.150	0.100
S5	0.200	0.200	0.200	0.100	0.100	0.100	0.100

**Table 2**

Input data used to calculate Material Reutilization Score (MRS), i.e. recycled content (%RC) and intrinsic recyclability (%IR); Material Circularity Indicator (MCI), i.e. %RC, recycling collection rate (%RCR), reuse rate (%ReR), yield during recycling, utility and life cycle based-indicators, i.e. mass of the body of the primary packaging and cup/lid, %RC, %RCR, %ReR and destination at disposal (% incineration with energy recovery and % going to landfill) for the selected packaging: SK (steel keg), AIC (aluminium can), OWGB (one-way glass bottle), RGB (refillable glass bottle) in the United Kingdom (UK) and India (IN).

Country	UK	UK	UK	UK	IN	IN	IN	IN
Packaging ID (size)	SK (50 l)	AIC (44 cl)	AIC (50 cl)	OWGB (33 cl)	RGB (65 cl)	RGB (33 cl)	AIC (50 cl)	AIC (44 cl)
Alternative n.	A1	A2	A3	A4	A1	A2	A3	A4
Material (lid/cup)	plastic	aluminium	aluminium	steel	steel	steel	aluminium	aluminium
mass [g]	88	2.30	2.66	2.00	2.00	2.00	2.73	2.22
Material (body)	steel	aluminium	aluminium	glass	glass	glass	aluminium	aluminium
mass [g]	12200	11.3	13.0	212	450	280	13.4	10.9
RC [%]	0 <sup>a</sup>	50 <sup>b</sup>	50 <sup>b</sup>	49 <sup>c</sup>	35 <sup>c</sup>	35 <sup>c</sup>	20 <sup>c</sup>	20 <sup>c</sup>
RCR [%]	60 <sup>d</sup>	63 <sup>d</sup>	63 <sup>d</sup>	61 <sup>d</sup>	20 <sup>e</sup>	20 <sup>e</sup>	87 <sup>f</sup>	87 <sup>f</sup>
Disposal [%]	Incineration with energy recovery (32.9) <sup>g</sup> Landfill (67.1) <sup>g</sup>				Incineration with energy recovery (6.4) <sup>e</sup> Landfill (93.6) <sup>e</sup>			
IR [%]	99.3	96.8	98.8	99	100	100	96.8	96.8
Yield [%]	84 <sup>h</sup>	97 <sup>i</sup>	97 <sup>i</sup>	100 <sup>h</sup>	100 <sup>h</sup>	100 <sup>h</sup>	97 <sup>i</sup>	97 <sup>i</sup>
Utility [-]	1	1	1	1	1	1	1	1
ReR [%]	98.7 <sup>l</sup>	n.a.	n.a.	n.a.	62 <sup>c</sup>	62 <sup>c</sup>	n.a.	n.a.

<sup>a</sup> No primary data available, thus assumption based on (Technical Secretariat for the Beer Pilot, 2015).

<sup>b</sup> (Stotz et al., 2017).

<sup>c</sup> Primary data.

<sup>d</sup> (The Brewers of Europe, 2018).

<sup>e</sup> (Ghosh, 2016).

<sup>f</sup> (Bertram et al., 2017).

<sup>g</sup> InstantLCA Tool based on Eurostat data (2015).

<sup>h</sup> (Rigamonti et al., 2009).

<sup>i</sup> (Niero and Olsen, 2016).

<sup>l</sup> (Technical Secretariat for the Beer Pilot, 2015).

different materials and packaging sizes. The list of packaging considered is reported in Table 2, for UK: i) 50 l steel keg (SK); ii) 44 centilitre (cl) aluminium can (AIC); iii) 50 cl AIC; iv) 33 cl one-way glass bottle (OWGB) and for India: i) 65 cl refillable glass bottle (RGB); ii) 33 cl RGB; iii) 33 cl AIC; iv) 50 cl AIC. The input data used to calculate the material circularity based- (MRS and MCI) and life cycle based-indicators (CC, ARD, AC, PM, WC) are also reported in Table 2. For MRS the parameters needed are: %RC and %IR (calculated considering the percentage of the component of the packaging, i.e. primary packaging and lid/cap that can be recycled after initial use). For MCI the parameters needed are: %RC, %RCR, % ReR, yield during recycling and utility (assumed equal to 1 in all cases). For the life cycle based-indicators the information needed are mass of the primary packaging and cup/lid, %RC, %RCR, %ReR and disposal at end-of-life (EoL), i.e. distribution between incineration with energy recovery and landfill.

### 3. Results and discussion

First the results of the stand-alone application of the two sets of indicators are presented (Section 3.1), then the outcomes of the coupling via MCDA is introduced (Section 3.2), and finally perspectives and limitations are outlined (Section 3.3).

#### 3.1. Stand-alone applications of material circularity- vs life cycle- based indicators

The results of the stand-alone application of the two types of indicators, i.e. material circularity based indicators (MRS and MCI) and life cycle based indicators (CC, ARD, AC, PM, WC) are reported in Table 3. Overall, for each country, the ranking of the packaging is the same within the LCA indicators, but differs when MCI and MRS are considered. In terms of life cycle based indicators in the UK case, the SK turns out as the less impacting packaging, followed by AIC (50 cl size slightly better than 44 cl) and OWGB. This ranking emerged also in previous studies on LCA of beer, where the full life cycle stages have been included. In the UK, the OWGB in 33 cl showed higher impacts

than AIC in 44 cl for global warming potential, water demand, abiotic depletion potential and acidification potential (Amienyo and Azapagic, 2016). In an Italian case, the returnable stainless SK showed lower impacts than the 33 cl OWGB in terms of global warming potential (Cimini and Moresi, 2016) and also considering impact categories at the endpoint level (Cordella et al., 2008). In the ranking of the least impacting packaging in the case of India, the 65 cl RGB ranks first, followed by the 50 cl AIC and then the same packaging with smaller sizes (i.e. 33 cl RGB and 44 cl AIC) in all impact categories, except AC, where the first two are inverted. These results are confirmed by previous LCA studies showing the positive influence on the environmental impacts of beverages of reusing glass bottles, e.g. for carbonated soft drinks in the UK market (Amienyo et al., 2012). Also the positive influence of packaging size has been proved, e.g. for beer in aluminium cans in the German market where the bigger the size the lower environmental impacts for a selected impact categories (Detzel and Mönckert, 2009).

The results of the material circularity based indicators (both MRS and MCI) show the opposite. For the UK, indeed, SK ranks as the worst packaging alternative (MCI = 0.55 and MRS = 66), followed by all the other packaging displaying the same performances (MCI = 0.60, and MRS = 81 for AIC both 44 cl and 50 cl and MRS = 82 for OWGB). Meanwhile for India, the ranking confirms the results of the life cycle based-indicators, at least in terms of packaging type, i.e. RGB (MRS = 78 and MCI = 0.63) better than AIC (MRS = 71 and MCI = 0.57), although no distinction between the different packaging size is provided. This is because for both MRS and MCI the mass of the packaging is not considered in the calculations.

#### 3.2. Coupling material circularity based- and life cycle based- indicators via MCDA

The application of the TOPSIS methodology with different weighting sets (see Table 4) shows that alternative 1 (A1, which is 50 l SK in the UK and the 65 cl RGB in IN) is dominating in all cases, i.e. has higher scores for all the scenarios. With regard to the ranking of the different alternatives, for UK it can be noted that two alternatives (AIC



**Table 3**

Results of the calculation of the indicators considered in the study: i) material circularity based-indicators: Material Reutilization Score (MRS) ranging from 0 to 100 and Material Circularity Indicator (MCI) ranging from 0 to 1 and ii) life cycle based-indicators: climate change (CC), abiotic resource depletion (ARD), acidification (AC), particulate matter (PM), water consumption (WC) for the selected packaging: SK (steel keg), AIC (aluminium can), OWGB (one-way glass bottle), RGB (refillable glass bottle) in the United Kingdom (UK) and India (IN). The colour coding shows the ranking from the best (green) to the worst (red) alternative.

Country	UK				IN			
Packaging ID	SK	AIC	AIC	OWGB	RGB	RGB	AIC	AIC
(size)	(50 l)	(44cl)	(50cl)	(33cl)	(65cl)	(33cl)	(50cl)	(44cl)
Alternative n.	A1	A2	A3	A4	A1	A2	A3	A4
MRS [-]	66	81	81	82	78	78	71	71
MCI [-]	0.55	0.60	0.60	0.60	0.63	0.63	0.57	0.57
CC [kg CO <sub>2</sub> eq/hl]	2.13E+00	2.97E+01	2.93E+01	7.30E+01	3.03E+01	3.82E+01	3.27E+01	4.22E+01
ARD [kg Sbeq/hl]	8.74E-04	2.22E-03	2.03E-03	2.65E-03	1.29E-03	2.40E-03	2.06E-03	2.95E-03
AC [mol H <sup>+</sup> eq/hl]	1.32E-02	1.48E-01	1.48E-01	5.09E-01	2.01E-01	2.51E-01	1.83E-01	2.34E-01
PM [kg PM <sub>2.5</sub> eq/hl]	1.86E-03	8.51E-03	8.48E-03	2.62E-02	1.07E-02	1.34E-02	1.06E-02	1.35E-02
WC [m <sup>3</sup> /hl]	1.70E-02	3.27E-01	3.28E-01	8.57E-01	3.33E-01	4.15E-01	3.38E-01	4.26E-01

in 44 cl and 50 cl, i.e. A2 and A3) present almost equal score in the life cycle based-indicators, as well as material circularity indicators (see Table 3) and hence TOPSIS scores display very small differences. For the Indian case, the two alternatives in the middle of the ranking present a remarkable difference in terms of life cycle based-indicators, i.e. 50 cl AIC (A3) has higher impact than 33 cl RGB (A2), see Table 3. The same holds for the material circularity based-indicators, but with opposite ranking, i.e. A2 better than A3 (see Table 3).

The stand-alone application of the material circularity based- and life cycle based- indicators presents a conflict and hence no alternative could be selected. This problem of univocally identifying the best performing alternative is solved by the implementation of the MCDA, clearly able to distinguish that A3 is the second most preferred option in all the weighting scenarios. The ranking obtained using TOPSIS in this case is in accordance with the LCA results. This shows that the influence of material circularity indicators is negligible in the final ranking. Such outcome can be interpreted with the help of Fig. 1, where the weighted normalized scores (obtained using Table 3 after vector normalization and weight multiplication) of the all alternatives for S1 (i.e. equal weighting) are plotted. In Fig. 1, the blue line indicates the PIS scores and green line indicates the NIS scores. The alternative that is closer or which follows the path of PIS is the most preferred alternative and the

alternative, which is closer to NIS, is the least preferred alternative. As it can be seen in Fig. 1 (showing results of S1), A1 resembles the pattern of PIS, A4 resembles the NIS, and hence they are identified as best and worst performing alternatives, respectively, in both UK and India case. A2 and A3 in UK case resembles each other and follows the path almost the middle of PIS and NIS and hence received the TOPSIS scores of about 0.6 (refer to Table 4). However, in the Indian case A3 follows the path of PIS more similar than A2 and hence received higher score of 0.639 compared to 0.299 score received by A2 in equal weighting scenario case (S1). This shows that the TOPSIS method with its unique mathematical Euclidian distance approach appropriately penalizes negatively the alternative, which is nearer to NIS and favours the alternative resembling the PIS. This is reflected in the scores obtained for A2 and A3 for the Indian case in all scenarios (see Table 4).

The results obtained by application of MCDA shows that the conflict among the indicators can be resolved when methods such as TOPSIS are applied. Overall, the application of different methods weighting scenarios does not change the ranking of the alternatives, thus confirming that the results are stable. Our proposal of coupling material circularity indicators with LCA indicators via MCDA demonstrate an advancement in the assessment of CE strategies at the product level.

**Table 4**

Results obtained from the application of the TOPSIS (Technique for Order by Similarity to Ideal Solution), i.e. ranking in the different weighting scenarios (S1-5) and considering the 4 alternatives (A1-A4) for UK and India (IN) for the selected packaging: SK (steel keg), AIC (aluminium can), OWGB (one-way glass bottle), RGB (refillable glass bottle) in the United Kingdom (UK) and India (IN). The colour coding shows the ranking from the best (green) to the worst (red) alternative.

UK										
Scenario No.	S1		S2		S3		S4		S5	
Packaging	Alternatives	Score	Alternatives	Score	Alternatives	Score	Alternatives	Score	Alternatives	Score
SK 50 l	A1	0.941	A1	0.902	A1	0.964	A1	0.961	A1	0.911
AIC 44cl	A2	0.643	A2	0.614	A2	0.667	A2	0.620	A2	0.632
AIC 50 cl	A3	0.653	A3	0.629	A3	0.676	A3	0.635	A3	0.640
OWGB 33cl	A4	0.059	A4	0.097	A4	0.036	A4	0.038	A4	0.088
India										
Scenario N.	S1		S2		S3		S4		S5	
Packaging	Alternatives	Score	Alternatives	Score	Alternatives	Score	Alternatives	Score	Alternatives	Score
RGB 65cl	A1	0.919	A1	0.942	A1	0.897	A1	0.934	A1	0.932
RGB 33cl	A2	0.299	A2	0.341	A2	0.270	A2	0.306	A2	0.345
AIC 44cl	A3	0.639	A3	0.592	A3	0.668	A3	0.617	A3	0.641
AIC 50 cl	A4	0.078	A4	0.056	A4	0.100	A4	0.064	A4	0.066

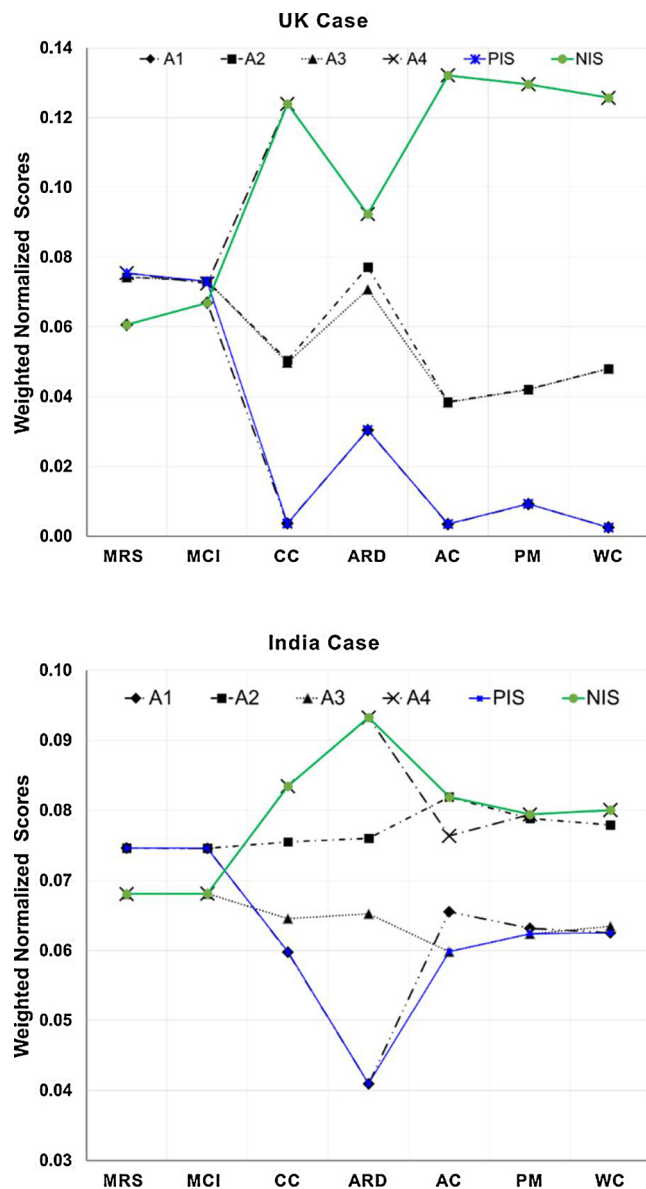


Fig. 1. Weighted normalized scores of all four alternatives (A1–A4) in the case of UK (on the top) and India (on the bottom) compared with Positive Ideal Solution (PIS) and Negative Ideal Solution (NIS) for Scenario 1 (equal weighting). Indicators considered are: Material Reutilization Score (MRS), Material Circularity Indicator (MCI), Climate Change (CC), Abiotic Resource Depletion (ARD), Acidification (AC), Particulate Matter (PM), Water Consumption (WC).

### 3.3. Perspectives and limitations

Our findings confirm the key role that life cycle thinking and its operative tool (LCA) play in the development of meaningful indicators for the CE with regard to the product level assessment (Elia et al., 2017). The LCA methodology has already proved capable to assess the environmental sustainability of the traditional linear approach for reducing resource use, i.e. resource efficiency (or narrowing resources flows according to Bocken et al. (2016) terminology), see e.g. (Huysman et al., 2015). At the same time, LCA can also assess the main CE approaches defined by Bocken et al., (2016), i.e. slowing resource loops, see e.g. (Bakker et al., 2014) and closing resource loops, see e.g. (Niero and Olsen, 2016). LCA is “by definition” meant to take into account two of the three necessary requirements for a CE strategy to guarantee absolute resource decoupling as listed by Kjaer et al. (2018),

i.e. “ensure net resource reduction” and “avoid burden shifting between life cycle stages”. However, although the potential of LCA as a decision support tool towards the evaluation of the environmental sustainability potential of CE approaches has been acknowledged (Haupt and Zschokke, 2017), its actual implementation is still not fully exploited. In the FMCG sector, indeed, most of the companies referring to CE in their corporate sustainability reports in 2016 have reported the use of LCA (and other footprint methodologies) to assess and/or monitor their environmental performances, but with no explicit link to CE activities (Stewart and Niero, 2018). LCA can be used in combination with other CE approaches, such as C2C to assess the environmental performances of C2C certified products (Llorach-Massana et al., 2015) and to quantify the progression in the C2C certification (Niero et al., 2016). Moreover, LCA can be combined with CE indicators, e.g. MCI as suggested by Lonca et al. (2018) to identify trade-offs between increasing material circularity and decreasing environmental burdens. The focus on the quantification of trade-offs issues between different sustainability dimensions connected with CE is crucial for a successful implementation of the concept (Niero and Hauschild, 2017b), as well as addressing the systemic dimension and potential CE rebound effects (Font Vivanco et al., 2018; Zink and Geyer, 2017).

However, due to the lack of consensus on the CE concept and given its different relationships with the sustainability concept (Geissdoerfer et al., 2017), it is essential to be able to assess CE strategies by means of indicators addressing several aspects. As we have shown, the MCDA methodology provides a key for such purpose, as it allows to combine different quantitative indicators and perspectives. In our study we explored the combination of material circularity based- and life cycle based- indicators via the TOPSIS methodology. We focus on a specific product category, i.e. beer packaging, as representative of the FMCG, but our proposal of coupling material circularity indicators with LCA indicators via MCDA can be applied to other relevant sectors for CE, such as electronics, building, water systems, food waste (EC et al., 2015b). In principle, our proposal can be applied not only at the micro, but also meso and macro levels, provided that a set of relevant indicators are selected. It can be relevant in the context of the monitoring framework for the circular economy proposed at the European level (European Commission, 2018), which aims at measuring progress towards a circular economy by means of 10 indicators addressing four aspects of the CE, namely i) production and consumption, ii) waste management, iii) secondary raw materials and iv) competitiveness and innovation (Mayer et al., 2018). As outlined by Elia et al. (2017) focusing on one single dimension (or a limited set of dimensions as in our case) represents a limitation in the assessment of CE models, and thus this is a limitation of our study. We indeed focused our analysis to a selection of material circularity and LCA indicators, but our approach of coupling several indicators via MCDA can be extended to incorporate a broader spectrum of CE indicators (Pauliuk, 2018), also including economic value (Di Maio et al., 2017; Linder et al., 2017) or in the case of MCI, the so-called complementary risk and impact indicators included in the MCI project (EMF and Granta Design, 2015). Moreover, the possibility of adopting different MCDA methodologies than TOPSIS could be explored, as it is recommended to apply more than one MCDA method to ascertain the results (Balasubramaniam et al., 2007). However, Kalbar et al. (2015, 2012) demonstrated that if the decision problem is structured appropriately, via formulating scenarios depicting the real-life situations or stakeholder preferences, application of many of the MCDA methods will result in the same outcome.

Finally, MCDA is particularly suited to address different quantitative and qualitative sustainability aspects and our findings confirm the role of CE and the relevance of index towards the achievement of sustainable development goals (Cucchiella et al., 2017; Gaustad et al., 2018; Haupt et al., 2017). Thus we recommend extending the life cycle perspective to the economic and social dimensions, e.g. through the Life Cycle Sustainability Assessment (LCSA) framework (Halog and Manik, 2011). The development of combined circularity (and longevity)

measures coupled with LCSA is also encouraged by Figge et al. (2018) as one of the most urgent research needs within CE metrics. The possibility of coupling different types of indicators is of particular relevance in view of the recent proposal submitted by the French National standardization body to the International Organization for Standardization to establish a new technical committee for the development of a management system related standard addressing the identification of metrics to be used by organizations to measure the progress made in the implementation of a CE project (AFNOR, 2018).

#### 4. Conclusions

In the “closed loop” circular economy research model introduced by Babbitt et al. (2018) in their editorial to the recent Special Issue of this journal on Sustainable Resource Management and the Circular Economy, the urgency of continually testing the real-world implementation of theoretical circular economy tools has been stressed. Our study contributes to the debate on the selection of the most suited metrics for CE implementation at the product level and adoption of framework for assessing product circularity with such metrics. We investigated the possibility of coupling different types of indicators addressing CE strategies at the product level via MCDA and validated our proposal with two cases in the packaging sector. We compared four packaging alternatives for beer in the UK and Indian markets, respectively, by means of two types of indicators: materials circularity based- (MCI and MRS) and life cycle based- (CC, ARD, AC, PM, WC) and found that the ranking changes according to the indicator set. Such conflict can be solved by coupling the indicators via MCDA, which supports the integration of different perspectives. Therefore, we recommend the use of TOPSIS (or similar methods) to make sense of the complementary CE indicators currently available and we encourage researchers to further explore the application of the MCDA framework and life cycle based-indicators (including the socio-economic dimension) to address CE trade-offs and rebound effects.

#### Acknowledgments

Monia Niero would like to thank the Carlsberg Foundation for funding the project “Absolute Circular Economy” (ACE) toolkit to support companies in the implementation of Circular Economy strategies from an Absolute environmental sustainability perspective”. The study reported in this paper builds on the oral contribution presented at SETAC (Society of Environmental Toxicology and Chemistry) Europe 28th Annual Meeting held in Rome (Italy) 13–17 May 2018.

#### References

- AFNOR, 2018. FORM 1 – Proposal for a New Field of Technical Activity. International Organization for Standardization, Geneva.
- Amienyo, D., Azapagic, A., 2016. Life cycle environmental impacts and costs of beer production and consumption in the UK. *Int. J. Life Cycle Assess.* 21, 492–509. <https://doi.org/10.1007/s11367-016-1028-6>.
- Amienyo, D., Gujba, H., Stichnothe, H., Azapagic, A., 2012. Life cycle environmental impacts of carbonated soft drinks. *Int. J. Life Cycle Assess.* 18, 77–92. <https://doi.org/10.1007/s11367-012-0459-y>.
- Babbitt, C.W., Gaustad, G., Fisher, A., Chen, W.Q., Liu, G., 2018. Closing the loop on circular economy research: from theory to practice and back again. *Resources, Conservation and Recycling*. Elsevier, pp. 1–2. <https://doi.org/10.1016/j.resconrec.2018.04.012>.
- Bakker, C., Wang, F., Huisman, J., den Hollander, M., 2014. Products that go round: exploring product life extension through design. *J. Clean. Prod.* 69, 10–16. <https://doi.org/10.1016/j.jclepro.2014.01.028>.
- Balasubramanian, A., Boyle, A.R., Voulvoulis, N., 2007. Improving petroleum contaminated land remediation decision-making through the MCA weighting process. *Chemosphere* 66, 791–798. <https://doi.org/10.1016/j.chemosphere.2006.06.039>.
- Behzadian, M., Khanmohammadi Otaghsara, S., Yazdani, M., Ignatius, J., 2012. A state-of-the-art survey of TOPSIS applications. *Expert Syst. Appl.* 39, 13051–13069. <https://doi.org/10.1016/j.eswa.2012.05.056>.
- Bertram, M., Ramkumar, S., Rechberger, H., Rombach, G., Bayliss, C., Martchek, K.J., Müller, D.B., Liu, G., 2017. A regionally-linked, dynamic material flow modelling tool for rolled, extruded and cast aluminium products. *Resour. Conserv. Recycl.* 125, 48–69. <https://doi.org/10.1016/j.resconrec.2017.05.014>.
- Björn, A., Hauschild, M.Z., 2013. Absolute versus relative environmental sustainability. *J. Ind. Ecol.* 17, 321–332. <https://doi.org/10.1111/j.1530-9290.2012.00520.x>.
- Blomsma, F., Brennan, G., 2017. The emergence of circular economy: a new framing around prolonging resource productivity. *J. Ind. Ecol.* 21, 603–614. <https://doi.org/10.1111/jiec.12603>.
- Bocken, N.M.P., de Pauw, I., Bakker, C., van der Grinten, B., 2016. Product design and business model strategies for a circular economy. *J. Ind. Prod. Eng.* 33, 308–320. <https://doi.org/10.1080/21681015.2016.1172124>.
- Bocken, N.M.P., Olivetti, E.A., Cullen, J.M., Potting, J., Lifset, R., 2017. Taking the circularity to the next level: a special issue on the circular economy. *J. Ind. Ecol.* 21, 476–482. <https://doi.org/10.1111/jiec.12606>.
- Braungart, M., Engelfried, J., 1992. An “intelligent product system” to replace “waste management”. *Fresenius Environ. Bull.* 1 (9), 613–619.
- British Standard, 2017. BS 8001:2017 Framework for Implementing the Principles of the Circular Economy in Organizations. Guide.
- Cimini, A., Moresi, M., 2016. Carbon footprint of a pale lager packed in different formats: assessment and sensitivity analysis based on transparent data. *J. Clean. Prod.* 112, 4196–4213. <https://doi.org/10.1016/j.jclepro.2015.06.063>.
- Cordella, M., Tugnoli, A., Spadoni, G., Santarelli, F., Zangrando, T., 2008. LCA case studies LCA of an Italian lager beer. *Int. J. Life Cycle Assess.* 13, 133–139.
- Cucchiella, F., D'Adamo, I., Gastaldi, M., Koh, S.L., Rosa, P., 2017. A comparison of environmental and energetic performance of European countries: a sustainability index. *Renew. Sustain. Energy Rev.* 78, 401–413. <https://doi.org/10.1016/j.rser.2017.04.077>.
- Detzel, A., Mönckert, J., 2009. Environmental evaluation of aluminium cans for beverages in the German context. *Int. J. Life Cycle Assess.* 14, 70–79. <https://doi.org/10.1007/s11367-008-0057-1>.
- Di Maio, F., Rem, P.C., Baldi, K., Polder, M., 2017. Measuring resource efficiency and circular economy: a market value approach. *Resour. Conserv. Recycl.* 122, 163–171. <https://doi.org/10.1016/j.resconrec.2017.02.009>.
- EC, 2015a. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. Closing the Loop - an EU Action Plan for the Circular Economy. European Commission, Brussels. <https://doi.org/10.1017/CBO9781107415324.004>.
- EC, 2015b. COM (2015) 614 Communication From the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. Closing the Loop - an EU Action Plan for the Circular Economy. COM (2015) 614 Communication From the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. Closing the Loop - an EU Action Plan for the Circular Economy.
- Elia, V., Gnani, M.G., Tornese, F., 2017. Measuring circular economy strategies through index methods: a critical analysis. *J. Clean. Prod.* 142, 2741–2751. <https://doi.org/10.1016/j.jclepro.2016.10.196>.
- EMF, 2015. Growth Within: A Circular Economy Vision for A Competitive Europe.
- EMF, 2013. Towards the circular economy. Opportunities for the consumer goods sector. Ellen MacArthur Foundation.
- EMF Granta Design, 2015. Circularity Indicators - An Approach to Measuring Circularity - Project overview.
- European Commission, 2018. A monitoring framework for the circular economy, Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. <https://doi.org/COM/2018/029final>.
- Evans, J., Bocken, N., 2013. Circular Economy Toolkit. Available online: <http://circularconomytoolkit.org> or [WWW Document]. Univ. Cambridge. Accessed 06.07.2018.
- Figge, F., Thorpe, A.S., Givry, P., Canning, L., Franklin-Johnson, E., 2018. Longevity and circularity as indicators of eco-efficient resource use in the circular economy. *Ecol. Econ.* 150, 297–306. <https://doi.org/10.1016/j.ecolecon.2018.04.030>.
- Font Vivanco, D., Sala, S., McDowall, W., 2018. Roadmap to rebound: how to address rebound effects from resource efficiency policy. *Sustain* 1–17. <https://doi.org/10.3390/su10062009>.
- Galatola, M., Pant, R., 2014. Reply to the editorial “product environmental footprint - breakthrough or breakdown for policy implementation of life cycle assessment?” Written by Prof. Finkbeiner (*Int. J. Life Cycle Assess.* 19(2):266–271). *Int. J. Life Cycle Assess.* 19, 1356–1360. <https://doi.org/10.1007/s11367-014-0740-3>.
- Gaustad, G., Krystofik, M., Bustamante, M., Badami, K., 2018. Circular economy strategies for mitigating critical material supply issues. *Resour. Conserv. Recycl.* 135, 24–33. <https://doi.org/10.1016/j.resconrec.2017.08.002>.
- Geissdoerfer, M., Savaget, P., Bocken, N.M.P., Hultink, E.J., 2017. The circular economy – a new sustainability paradigm? *J. Clean. Prod.* 143, 757–768. <https://doi.org/10.1016/j.jclepro.2016.12.048>.
- Ghosh, S.K., 2016. Sustainable SWM in developing countries focusing on faster growing economies, India and China. *Procedia Environ. Sci.* 35, 176–184. <https://doi.org/10.1016/j.proenv.2016.07.073>.
- Gogate, N.G., Kalbar, P.P., Raval, P.M., 2017. Assessment of stormwater management options in urban contexts using multiple attribute decision-making. *J. Clean. Prod.* 142, 2046–2059. <https://doi.org/10.1016/j.jclepro.2016.11.079>.
- Greco, S., Ehrgott, M., Rui Figueira, J., 2016. Multiple criteria decision analysis. *Multiple Criteria Decision Analysis. State of the Art Surveys*, 2nd ed. Springer <https://doi.org/10.1007/978-1-4939-3094-4>.
- Griffiths, P., Cayzer, S., 2016. Design of indicators for measuring product performance in the circular economy. 3rd International Conference on Sustainable Design and Manufacturing SDM 2016 307–321.
- Guitouni, A., Martel, J.M., 1998. Tentative guidelines to help choosing an appropriate



- MCD method. *Eur. J. Oper. Res.* 109, 501–521. [https://doi.org/10.1016/S0377-2217\(98\)00073-3](https://doi.org/10.1016/S0377-2217(98)00073-3).
- Halog, A., Manik, Y., 2011. Advancing integrated systems modelling framework for life cycle sustainability assessment. *Sustainability* 3, 469–499. <https://doi.org/10.3390/su3020469>.
- Haupt, M., Vadenbo, C., Hellweg, S., 2017. Do we have the right performance indicators for the circular economy? Insight into the swiss waste management system. *J. Ind. Ecol.* 21, 615–627. <https://doi.org/10.1111/jiec.12506>.
- Haupt, M., Zschokke, M., 2017. How can LCA support the circular economy?—63rd discussion forum on life cycle assessment, Zurich, Switzerland, November 30, 2016. *Int. J. Life Cycle Assess.* 22, 832–837. <https://doi.org/10.1007/s11367-017-1267-1>.
- Hauschild, M.Z., Goedkoop, M., Guinée, J., Heijungs, R., Huijbregts, M., Joliet, O., Margni, M., Schryver, A., Humbert, S., Laurent, A., Sala, S., Pant, R., 2013. Identifying best existing practice for characterization modeling in life cycle impact assessment. *Int. J. Life Cycle Assess.* 18, 683–697. <https://doi.org/10.1007/s11367-012-0489-5>.
- Homrich, A.S., Galvão, G., Abadia, L.G., Carvalho, M.M., 2018. The circular economy umbrella: trends and gaps on integrating pathways. *J. Clean. Prod.* 175, 525–543. <https://doi.org/10.1016/j.jclepro.2017.11.064>.
- Huysman, S., Sala, S., Mancini, L., Ardente, F., Alvarenga, R.F., De Meester, S., Mathieux, F., Dewulf, J., 2015. Toward a systematized framework for resource efficiency indicators. *Resour. Conserv. Recycl.* 95, 68–76. <https://doi.org/10.1016/j.resconrec.2014.10.014>.
- Kalbar, P.P., Karmakar, S., Asolekar, S.R., 2012. Selection of an appropriate wastewater treatment technology: a scenario-based multiple-attribute decision-making approach. *J. Environ. Manage.* 113, 158–169. <https://doi.org/10.1016/j.jenvman.2012.08.025>.
- Kalbar, P.P., Karmakar, S., Asolekar, S.R., 2015. Selection of wastewater treatment alternative: significance of choosing MADM method. *Environ. Eng. Manag. J.* 14, 1011–1020.
- Kalbar, P.P., Birkved, M., Karmakar, S., Nygaard, S.E., Hauschild, M., 2017a. Can carbon footprint serve as proxy of the environmental burden from urban consumption patterns? *Ecol. Indic.* 74, 109–118. <https://doi.org/10.1016/j.ecolind.2016.11.022>.
- Kalbar, P.P., Birkved, M., Nygaard, S.E., Hauschild, M., 2017b. Weighting and aggregation in life cycle assessment: do present aggregated single scores provide correct decision support? *J. Ind. Ecol.* 21, 1591–1600. <https://doi.org/10.1111/jiec.12520>.
- Kalbar, P.P., Birkved, M., Hauschild, M., Kabins, S., Nygaard, S.E., 2018. Environmental impact of urban consumption patterns: drivers and focus points. *Resour. Conserv. Recycl.* 137, 260–269. <https://doi.org/10.1016/j.resconrec.2018.06.019>.
- Kirchherr, J., Reike, D., Hekkert, M., 2017. Conceptualizing the circular economy: an analysis of 114 definitions. *Resour. Conserv. Recycl.* 127, 221–232. <https://doi.org/10.1016/j.resconrec.2017.09.005>.
- Kjaer, L.L., Pigosso, D.C.A., Niero, M., Bech, N.M., Mcaloon, T.C., 2018. Product/Service-systems for a circular economy: the route to decoupling economic growth from resource consumption? *J. Ind. Ecol.* <https://doi.org/10.1111/jiec.12747>.
- Korhonen, J., Honkasalo, A., Seppälä, J., 2018. Circular economy: the concept and its limitations. *Ecol. Econ.* 143, 37–46. <https://doi.org/10.1016/j.ecolecon.2017.06.041>.
- Linder, M., Sarasini, S., van Loon, P., 2017. A metric for quantifying product-level circularity. *J. Ind. Ecol.* 21, 545–558. <https://doi.org/10.1111/jiec.12552>.
- Llorach-Massana, P., Farreny, R., Oliver-Solà, J., 2015. Are Cradle to Cradle certified products environmentally preferable? Analysis from an LCA approach. *J. Clean. Prod.* 93, 243–250. <https://doi.org/10.1016/j.jclepro.2015.01.032>.
- Lonca, G., Mugg, R., Hugue, T., Bernard, S., Margni, M., 2018. A bi-dimensional assessment to measure the performance of circular economy: a case study of tires End-of-life management Geoffrey. In: Benetto, E., Gericke, K., Guiton, M. (Eds.), *Designing Sustainable Technologies, Products and Policies*, pp. 33–42. <https://doi.org/10.1007/978-3-319-66981-6>.
- Mayer, A., Haas, W., Wiedenhofer, D., Krausmann, F., Nuss, P., Blengini, G.A., 2018. Measuring progress towards a circular economy: a monitoring framework for economy-wide material loop closing in the EU28. *J. Ind. Ecol.* 0, 1–15. <https://doi.org/10.1111/jiec.12809>.
- Niero, M., Hauschild, M.Z., 2017a. Which role for Life Cycle Thinking in the definition of meaningful indicators for the circular economy? In: *Proceedings of the 11th Italian LCA Network Conference (Atti Del XI Convegno Della Rete Italiana LCA: Resource Efficiency and Sustainable Development Goals: The Role of Life Cycle Thinking)*. Siena, 22–23 Giugno 2017, Valentina Niccolucci, Arianna Dominici Loprieno, Simone Maranghi, Simona Scalbi. pp. 11–19.
- Niero, M., Hauschild, M.Z., 2017b. Closing the loop for packaging: finding a framework to operationalize circular economy strategies. *Procedia CIRP*. <https://doi.org/10.1016/j.procir.2016.11.209>.
- Niero, M., Olsen, S.I., 2016. Circular economy : to be or not to be in a closed product loop? A Life Cycle Assessment of aluminium cans with inclusion of alloying elements. *Resour. Conserv. Recycl.* 114, 18–31. <https://doi.org/10.1016/j.resconrec.2016.06.023>.
- Niero, M., Schmidt-Rivera, X.C., 2018. The role of life cycle sustainability assessment in the implementation of circular economy principles in organizations. *Procedia CIRP*. <https://doi.org/10.1016/j.procir.2017.11.022>.
- Niero, M., Negrelli, A.J., Hoffmeyer, S.B., Olsen, S.I., Birkved, M., 2016. Closing the loop for aluminium cans: life Cycle Assessment of progression in Cradle-to-Cradle certification levels. *J. Clean. Prod.* 126, 352–362. <https://doi.org/10.1016/j.jclepro.2016.02.122>.
- Pauliuk, S., 2018. Critical appraisal of the circular economy standard BS 8001:2017 and a dashboard of quantitative system indicators for its implementation in organizations. *Resour. Conserv. Recycl.* 129, 81–92. <https://doi.org/10.1016/j.resconrec.2017.10.019>.
- Pires, A., Chang, N., Bin, Martinho, G., 2011. An AHP-based fuzzy interval TOPSIS assessment for sustainable expansion of the solid waste management system in Setúbal Peninsula. Portugal. *Resour. Conserv. Recycl.* 56, 7–21. <https://doi.org/10.1016/j.resconrec.2011.08.004>.
- Rigamonti, L., Grosso, M., Sunseri, M.C., 2009. Influence of assumptions about selection and recycling efficiencies on the LCA of integrated waste management systems. *Int. J. Life Cycle Assess.* 14, 411–419. <https://doi.org/10.1007/s11367-009-0095-3>.
- Saidani, M., Yannou, B., Leroy, Y., Cluzel, F., 2017. How to assess product performance in the circular economy? Proposed requirements for the design of a circularity measurement framework. *Recycling* 2, 6. <https://doi.org/10.3390/recycling2010006>.
- Seager, T.P., Linkov, I., 2008. Coupling multicriteria decision analysis and life cycle assessment for nanomaterials. *J. Ind. Ecol.* 12, 282–285. <https://doi.org/10.1111/j.1530-9290.2008.00048.x>.
- Seppälä, J., Basson, L., Norris, G.A., 2001. Decision analysis frameworks for life-cycle impact assessment. *J. Ind. Ecol.* 5, 45–68. <https://doi.org/10.1162/10881980160084033>.
- Sohn, J.L., Kalbar, P.P., Birkved, M., 2017. Life cycle based dynamic assessment coupled with multiple criteria decision analysis: a case study of determining an optimal building insulation level. *J. Clean. Prod.* 162, 449–457. <https://doi.org/10.1016/j.jclepro.2017.06.058>.
- Steinmann, Z.J.N., Schipper, A.M., Hauck, M., Huijbregts, M.A.J., 2016. How many environmental impact indicators are needed in the evaluation of product life cycles? *Environ. Sci. Technol.* 50, 3913–3919. <https://doi.org/10.1021/acs.est.5b05179>.
- Stewart, R., Niero, M., 2018. Circular economy in corporate sustainability strategies: a review of corporate sustainability reports in the fast-moving consumer goods sector. *Bus. Strateg. Environ.* <https://doi.org/10.1002/bse.2048>.
- Stotz, P.M., Niero, M., Bey, N., Paraskevas, D., 2017. Environmental screening of novel technologies to increase material circularity: a case study on aluminium cans. *Resour. Conserv. Recycl.* 127. <https://doi.org/10.1016/j.resconrec.2017.07.013>.
- Suárez Silgado, S., Calderón Valdiviezo, L., Gassó Domingo, S., Roca, X., 2018. Multi-criteria decision analysis to assess the environmental and economic performance of using recycled gypsum cement and recycled aggregate to produce concrete: the case of Catalonia (Spain). *Resour. Conserv. Recycl.* 133, 120–131. <https://doi.org/10.1016/j.resconrec.2017.11.023>.
- Technical Secretariat for the Beer Pilot, 2015. PEF screening report in the context of the EU Product Environmental Footprint Category Rules (PEFCR) Pilots - Version 3.3. pp. 1–127.
- The Brewers of Europe, 2018. PEF for Beer Final version. pp. 1–88.
- United Nations, 2015. Paris Agreement. Paris, France. <https://doi.org/10.1017/s0020782900004253>.
- Van Hoof, G., Vieira, M., Gausman, M., Weisbrod, A., 2013. Indicator selection in life cycle assessment to enable decision making: issues and solutions. *Int. J. Life Cycle Assess.* 18, 1568–1580. <https://doi.org/10.1007/s11367-013-0595-z>.
- Walker, S., Coleman, N., Hodgson, P., Collins, N., Brimacombe, L., 2018. Evaluating the environmental dimension of material efficiency strategies relating to the circular economy. *Sustain* 10, 1–14. <https://doi.org/10.3390/su10030666>.
- Zink, T., Geyer, R., 2017. Circular economy rebound. *J. Ind. Ecol.* 21, 593–602. <https://doi.org/10.1111/jiec.12545>.