# A Review of Circularity Performance Assessment Methods

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**Abstract**: Globalization and consumerism behaviours are depleting natural resources and downgrading the environment. This negative perspective is pushing worldwide the interest on Circular Economy (CE). CE wants to eliminate wastes, retain value from products and materials, foster the use of renewable energies and eliminate toxic chemicals. However, it is still not fully explained how to measure and assess the circularity performance of a system. To this aim, the paper wants to detect, through a systematic literature review, the existing CE performance assessment methods, by describing their relations with both product lifecycle stages and other methods.

**Keywords**: Circular Economy; Circularity Performance Assessment; Methodology; Literature Review.

## 1. Introduction

Circular Economy (CE) is a quite recent and discussed concept (Winans, Kendall and Deng, 2017). Together with academics and associations (The Ellen MacArthur Foundation, 2013), also companies and policy-makers (Suárez-Eiroa *et al.*, 2019) demonstrated their interest in this paradigm, especially in Europe and China. Today, CE is a re-known concept in literature, used for replacing traditional linear economies, based on virgin materials and mono-use products. In this context, CE is considered an industrial system, pursuing either restoration or regeneration, aimed at closing the product lifecycle loop (The Ellen MacArthur Foundation, 2013). A recent research (F. Bonciu, 2014) stated that a sustainable economic growth based on linear production models is not feasible in a planet with finite resources and a limited capacity to absorb wastes. Given that, the management of a circular system is more complex. Therefore, resources need to be measured in order to be able to adequately assess and manage them in circular systems. However, the literature doesn't provide enough interest on CE performance assessment methods. To this aim, the intent of this paper is understanding which methods are used in literature to assess CE performances. The article is structured as follows. Section 2 presents the research objectives. Section 3, after a brief introduction about the research methodology, provides results of the literature analysis, by listing circularity performance assessment methods and trying to understand how and in which context they have been adopted. Section 4 concludes the paper discussing results and providing remarks and future research streams.

## 2. Research objectives

The main objectives of this literature review are: 1) investigating which are the existing CE performance assessment methods 2) understanding how and in which contexts they have been adopted. The next section presents the research method used to achieve them.

## 3. Literature review

A literature review on scientific articles published up to the second quarter of 2018 and gathered from Science Direct® and Scopus® has been carried out. The keywords "circular economy" and "end of life", were combined with "performance", "assessment" and "methodology" in a total of six searches, without any document type, timeframe or field content limitation. Searches led to 986 results. Moreover, 18 documents were detected through cross-referencing processes and 9 through hand search. 5 more documents have been recommended by experts. After having excluded: i) grey literature, ii) non-English contributions, iii) redundancies, iv) unfitting papers (by title/abstract check) and v) unfitting papers (by full-text check), a total amount of 53 articles have been analysed. Subsequently, by adopting further relevance and quality criteria, a total amount of 45 documents were selected as reference literature. An assessment of results shows that 73.3% of these papers have been published from 2016 onwards. In terms of nationality, the highest number of contributions come from European countries (57,8%), followed by China. Lots of contributions (40 out of 45) provide not only a theoretical view on circularity aspects, but also a context (or industry) where applying the proposed frameworks and methods. Basing on that, contributions can be divided between those focused on intra-company links (30 papers) and those focused on inter-company ones (10 papers). In the first case, the analysis focused on specific sectors, like metallurgy (10%), automotive (10%), electronics (10%), food (10%), construction (10%), plastics (5%) and others. In the second case, wider and complex systems have been assessed, like urban areas (12,5%), industrial parks (7,5%) and whole supply chains (5%).

### 3.1 Circularity performance assessment methods

Generally, all the assessed papers started from the selection and mix of already existing methods, frameworks, indexes or approaches, by proposing new ones, more suitable for circular systems. All of them were heeded on measuring only specific aspects of CE. This premise allowed the selection of certain methodologies. The final set of 45 papers is reported in the following Table 1.

**Table 1: Existing CE performance assessment methods**

| **Authors** | **Method** | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | **DEA/ I-O** | **DfX/ GL** | **LCA/ LCI/ LCIA** | **MCDM/ fuzzy methods** | **Em/ Ex** | **Simulation/ DES** | **MFA/ MCA/ MFCA** | **Others** |
| (Mardani et al., 2017) | x | | | | | | | |
| (Oliveira et al., 2018) | | x | | | | | | |
| (Han et al., 2017) | | | | | | | | SNA |
| (Petit et al., 2018) | | | x | x | | | | CSR |
| (Pan et al., 2016) | | | | | x | | | |
| (Awasthi et al., 2018) | | | | | | | | RM |
| (Expósito and Velasco, 2018) | x | | | | | | | |
| (Sénéchal, 2017) | | | | | | x | | |
| (Akanbi et al., 2018) | | | | | | | | BWPE |
| (Gbededo et al., 2018) | | | x | | | x | | SPD, SPA |
| (Angelis-Dimakis et al., 2016) | | | x | | | | | |
| (Pauliuk, 2018) | | | x | | | | x | |
| (Yang et al., 2011b) | | | | | | | | FA |
| (Yang et al., 2011a) | | | | | | | | FA |
| (Li, 2011) | | | | | | | | ANP |
| (Laso et al., 2018) | | | x | | | | | |
| (Huysman et al., 2017) | | | x | | x | | | |
| (Ng and Martinez Hernandez, 2016) | | | | x | | | | PM |
| (Biganzoli et al., 2018) | | | x | | | | | |
| (Grimaud et al., 2017) | | x | x | | | | x | |
| (Hadzic et al., 2018) | | | x | | | | | |
| (Laso et al., 2016) | | | x | | | | | |
| (Martin et al., 2017) | | | x | | | | | |
| (Fregonara et al., 2017) | | | x | | | | | REA |
| (Franklin-Johnson et al., 2016) | | | | | | | x | LBM |
| (Pagotto and Halog, 2015) | x | | | | | | x | |
| (Voskamp et al., 2016) | | | | | | | x | |
| (Shen et al., 2013) | | | | x | | | | |
| (Kazancoglu et al., 2018) | | | | x | | | | |
| (Olugu and Wong, 2012) | | | | x | | | | |
| (Motevali Haghighi et al., 2016) | x | | | | | | | BSC |
| (Eastwood and Haapala, 2015) | | | x | | | | | |
| (Park et al., 2016) | x | | x | | x | | | |
| (Kamali et al., 2018) | | | | | | | | AHP |
| (Jamali-Zghal et al., 2015) | | | x | | x | | | |
| (Berzi et al., 2016) | | | | | | | | SA |
| (Xu et al., 2018) | | | | x | | | | |
| (Iakovou et al., 2009) | | | | x | | | | |
| (Delogu et al., 2017) | | | | | | | | SA |
| (Akinade et al., 2017) | | x | | | | | | |
| (Santini et al., 2010) | | x | | | | | | |
| (Lee et al., 2014) | | x | | | | | | |
| (Issa et al., 2015) | | x | | | | | | |
| (Wibowo and Grandhi, 2017) | | | | x | | | | |
| (Favi et al., 2017b) | | x | | | | | | |
| **Total** | **5** | **7** | **15** | **8** | **4** | **2** | **5** | **15** |

DEA= Data Envelopment Analysis, I-O= Input-Output, DfX= Design for X, GL= Guidelines, LCA=Life Cycle Assessment, LCI= Life Cycle Inventory, LCIA= Life Cycle Impact Assessment, MCDM= Multi Criteria Decision Methods, Em= Emergy approach, Ex= Exergy approach, DES= Discrete Event Simulation, MFA= Material Flow Analysis, MCA= Material Cost Analysis, MFCA= Material Flow Cost Accounting, SNA= Social Network Analysis, CSR/P= Corporate Social Responsibility/Performance, RM= Regression Model, BWPE= BIM-based Whole-life Performance Estimator, SPD= Sustainable Product Development, SPA= Sustainable Performance Assessment, FA= Factor Analysis, AHP/ANP= Analytic Hierarchic/Network Process, PM=Process Modelling, REA= Real Estate Appraisal, LBM= Longevity Based Method, BSC= Balanced Score Card, SA= Sensitivity Analysis

#### 3.2.1 Life Cycle Assessment

The most common methodology is Life Cycle Assessment (LCA) (Eastwood and Haapala, 2015; Jamali-Zghal, Lacarrière and Le Corre, 2015; Angelis-Dimakis, Alexandratou and Balzarini, 2016; Laso et al., 2018; Park, Egilmez and Kucukvar, 2016; Laso et al., 2016; Martin et al., 2017; Fregonara et al., 2017; Grimaud, Perry and Laratte, 2017; Huysman et al., 2017; Biganzoli, Rigamonti and Grosso, 2018; Pauliuk, 2018; Petit, Sablayrolles and Yannou-Le Bris, 2018; Gbededo, Liyanage and Garza-Reyes, 2018; Hadzic, Voca and Golubic, 2018). Several examples are present in literature. (Angelis-Dimakis, Alexandratou and Balzarini, 2016) described a methodological framework for assessing the eco-efficient use of water in the textile industry. (Pauliuk, 2018) discussed about a dashboard of quantitative indexes (based on both Material Flow Analysis (MFA), Material Flow Cost Accounting (MFCA) and LCA) for assessing alternative CE strategy in organizations. Laso et al. (2016) assessed the treatment and valorisation of anchovy wastes, through LCA, comprehensive of its sub-phases LCI and LCIA, subsequently upgraded in a two-step eco-efficiency assessment method for the fish canning industry (Laso et al., 2018). Hadzic et al. (2018) proposed a LCA-based assessment of wastes in an urban context. (Martin et al., 2017) adopted LCA for evaluating the environmental benefits coming from by-products in biofuels. Biganzoli et al. (2018) assessed through LCA the environmental impacts of reusing intermediate bulk containers. Fregonara et al. (2017) combined different approaches for developing a decision-making tool supporting designers in the construction industry. Similarly, (Grimaud, Perry and Laratte, 2017) supported designers through a decision-support tool based on LCA, MFA and Environmental Technology Verification (ETV). (Eastwood and Haapala, 2015) exploited LCI for developing a product sustainability assessment methodology at the design stage. (Park, Egilmez and Kucukvar, 2016) proposed an ecological performance assessment framework based on Eco-LCA, ReCiPe and linear programming. (Petit, Sablayrolles and Yannou-Le Bris, 2018) used a combination of LCA, Corporate Social Responsibility (CSR) and Multiple-Attribute Decision-Making (MADM) for conceptualizing a value chain sustainability assessment framework.

As a result, LCA often coupled with other methods, results to be used for evaluating materials and other resources (e.g. energy and pollution), by focusing mainly on BoL and EoL stages, with an environmental and economic perspective.

#### 3.2.2 MCDM approaches and fuzzy logic

Considering the complexity of circular systems, different authors (Iakovou et al., 2009; Olugu and Wong, 2012; Shen et al., 2013; Ng and Martinez Hernandez, 2016; Wibowo and Grandhi, 2017; Kazancoglu, Kazancoglu and Sagnak, 2018; Petit, Sablayrolles and Yannou-Le Bris, 2018; Xu et al., 2018) adopted multi-criteria and fuzzy logic-based approaches. (Ng and Martinez Hernandez, 2016) proposed a decision-making framework combining multi-criteria analysis and process modelling, by considering both economic and energy ratios. (Shen et al., 2013) exploited a fuzzy multi-criteria approach for evaluating supplier's performances in green supply chains. Expert fuzzy rule-based approaches have been adopted also by (Olugu and Wong, 2012) for implementing a closed-loop supply chain performance measurement framework. Wibowo and Grandhi (2017) used multi-criteria decision-making for evaluating EoL products recovery performances in a reverse supply chain. Xu et al., (2018) applied a capacity-based Multi-Criteria Decision Making (MCDM) approach to Wastes from Electronic and Electrical Equipment (WEEE) recycling sector. Iakovou et al. (2009) proposed a "Multi-criteria Matrix" framework for managing electronic wastes. Kazancoglu et al. (2018) identified a criterion for assessing Green Supply Chains (GSC) in terms of environmental, economic, financial, operational, logistic, organizational and marketing performances.

Wrapping up, MCDM and fuzzy methods result to be rarely coupled with other methodologies for measuring circular performances. Moreover, the focus is on the BoL stage.

#### 3.2.3 Design for X and guidelines

Other authors focused on the design stage (Santini et al., 2010; Lee, Lu and Song, 2014; Issa et al., 2015; Akinade et al., 2017; Favi et al., 2017; Grimaud, Perry and Laratte, 2017; Oliveira, França and Rangel, 2018), by using Design for X (DfX) approaches and guidelines for enabling CE. Oliveira et al. (2018) proposed strategic guidelines for CE and a list of generic CE performance parameters. Akinade et al. (2017) described 43 Design for Disassembly (DfD) Critical Success Factors (CSF) for the construction industry. Santini et al. (2010) implemented a disassembly and composition analysis for EoL vehicles supported by Design for Recycling. Lee et al. (2014) defined an EoL Index, based on the Design for End-of-Life (DfEoL) approach, for comparing design alternatives in terms of EoL performances. Issa et al. (2015) identified the Environmental Performance Indicators (EPI) of lifecycle phases, environmental aspects and measuring procedure (absolute or relative). Favi et al. (2017) used DfX approaches (DfD, DfEoL) for providing new metrics for product EoL assessment and management.

Briefly, DfX approaches contribute to the circularity performance assessment, often coupled with LCA and MFA. They are used mostly during Design & Development (D&D) of products and, sometimes, provide also guidelines for a strategic evaluation at BoL and EoL stages. The environmental perspective (e.g. in terms of products material composition) is the focus of these approaches.

#### 3.2.4 DEA and input-output models

Other experts decided to measure flows of variables in circular systems. Some of them (Pagotto and Halog, 2015; Motevali Haghighi, Torabi and Ghasemi, 2016; Park, Egilmez and Kucukvar, 2016; Mardani et al., 2017; Expósito and Velasco, 2018) used input-output (I-O) methods, as Data Envelopment Analysis (DEA). Others (Franklin-Johnson, Figge and Canning, 2016; Voskamp et al., 2016; Grimaud, Perry and Laratte, 2017; Pauliuk, 2018) recurred to MFA and MFCA. Mardani et al. (2017) adopted DEA for analysing energy efficiency issues. (Expósito and Velasco, 2018) proposed a multiple-output DEA model for the MSW recycling sector. (Pagotto and Halog, 2015) combined DEA, I-O methods and MFA for evaluating eco-efficiency performances. Motevali Haghighi et al. (2016) developed a hybrid Balanced Score Card (BSC) - DEA framework for evaluating performances of sustainable supply chains.

This kind of approaches aim at measuring all the possible variables involved in a system, from production up to disposal. Here, the environmental perspective is the most discussed one.

### 3.2.5 Material flow analysis

From the MFA view, few examples were gathered from the literature. (Franklin-Johnson, Figge and Canning, 2016), by combining longevity-based methods and MFA, proposed resource duration as a new index for assessing environmental performances linked to CE. Voskamp et al. (2016) modified the MFA method for conducting a comprehensive assessment of urban metabolism, based on the concepts of Direct Material Input (DMI) and Domestic Material Consumption (DMC).
This approach, like DEA/I-O methods, can consider and evaluate environmentally and economically all the variables involved in a system along the entire lifecycle (almost neglecting the product D&D).

### 3.2.6 Emergy and exergy-based approaches

Some works focused on measuring just one of the variables (e.g. energy) involved in a system, for example through concepts as emergy and exergy (Jamali-Zghal, Lacarrière and Le Corre, 2015; Pan et al., 2016; Huysman et al., 2017). From the first side, (Pan et al., 2016) presented several indexes for evaluating recycling and reuse benefits in industrial parks. (Huysman et al., 2017) introduced the Circular economy Performance Indicator (CPI), defined as the ratio of the actual environmental benefit coming from current waste treatment options over the ideal environmental benefit (expressed in terms of natural resources consumption). From the second side, (Jamali-Zghal, Lacarrière and Le Corre, 2015) combined LCA and emergy, by presenting the Exergetic Life Cycle Assessment (ELCA), expressed as the mix of three sustainability ratios (resource efficiency, quality and eco-design ratios).
These energy-based approaches have been often paired with LCA methods for measuring environmental impacts, mainly energy variables. Moreover, they are focused on the entire lifecycle, except product D&D.

### 3.2.7 Discrete event simulation

Other works used simulation (e.g. Discrete Event Simulation (DES) and process simulation), by combining it with LCA (Sénéchal, 2017; Gbededo, Liyanage and Garza-Reyes, 2018). Gbededo et al. (2018) applied DES and holistic Life Cycle Sustainability Assessment (LCSA) to Sustainable Product Development (SPD) and Sustainable Performance Assessment (SPA). Sénéchal (2017) used the eco-value analysis matrix for implementing a framework (and dashboard) for measuring performances of Sustainable Condition-Based Maintenance (SCBM).
In this case, it is difficult to understand DES/simulation methods' focus, both in terms of sustainable dimensions, variables and lifecycle stages.

### 3.2.8 Other approaches

Some assessments in the construction industry used industry-specific methods for developing a salvage performance model of building materials (Akanbi et al., 2018), combining real estate appraisal and LCA (Fregonara et al., 2017). Similarly, (Kamali, Hewage and Milani, 2018) adopted AHP for developing a sustainability assessment framework for modular buildings. Fregonara et al. (2017) implemented an economic/environmental index a decision-making tool supporting designers. Kamali et al. (2018) detected different areas contributing to the lifecycle sustainability of buildings and, for each of them, several Sustainability Performance Criteria (SPC) have been identified. Li (2011) used AHP for conducting a comprehensive evaluation of CE performances of eco-industrial parks. Yang et al. (2011a, 2011b) used factor analysis for building a complex evaluation index of CE, composed of indexes pertaining to the three aspects of sustainability. A sensitivity analysis based on different dismantling scenarios has been performed by (Delogu et al., 2017), for calculating recyclability and recoverability rates of vehicles. Similarly, Berzi et al. (2016) used ISO 22628 and UNIFE assessments for proposing a method evaluating end-of-life performances. (Han et al., 2017) exploited SNA for studying how CE measures can support the aluminium industry. Awasthi et al. (2018) used regression models for investigating the relation between e-waste quantities and economic increases.

This heterogeneous set of approaches attempt to measure all the variables of a system, during the whole lifecycle and under environmental, economic and social perspectives. A specific focus is on products material composition, assessed from an EoL view.

## 4. Discussion and conclusions

This paper discussed about a literature review aimed at understanding which methods are used to evaluate the performance of circular systems and in which contexts they have been used for. LCA-based approaches, together with MCDM and DfX, result to be the most common methods for assessing circularity performances. Selected documents highlighted a strong inclination towards the environmental and economic dimensions of sustainability. In addition, variables deserving more attention in terms of circularity performance, have been identified in materials (constituting the product), energy and other resources (used to make a product). Again, materials deserved a high interest, corroborating the relevance of such type of variables in circular systems characterized by continuous flows of technical and biological materials (The Ellen MacArthur Foundation, 2015). Indeed, according to the CE concept, the adopted methodologies were supposed to measure materials involved in the system, sometimes attempting to consider the related quantity and type of energy used and generated pollution. Finally, a propensity to measure the circular performance either during BoL or EoL phases has been observed. Indeed, an evident lack of interest towards the analysis of the MoL phase has been noticed, even if in many cases researchers attempted to combine many lifecycle stages together. The analysis confirms that different methodologies can be adopted for measuring different aspects of a circular system. DfX and guidelines are used to enhance the product development, by supporting the change from a linear lifecycle to a circular one. LCA, MFA, DEA/I-O, MCDM and DES can support the evaluation of variables involved in the system along the lifecycle, by focusing most on the rest of the lifecycle, from production up to disposal. The conducted literature analysis highlights that methodologies capable to perform an overall evaluation of CE benefits are still missing. This happens since it is very complex for researchers to consider the huge number of variables involved along the entire lifecycle of a system. To this aim, a set of indicators is needed to assess CE (Moraga *et al.*, 2019). Supported by methods like LCA and MFA, these indexes would focus either on wastes and material flows involved in the systems or on recycling rates. Based on the obtained results, further researches can be carried on. To this aim, a positioning framework could be useful to: i) map selected methods, ii) identify gaps and iii) provide theoretical directions about dimensions to be considered for developing new methodologies capable to evaluate circularity.

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