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Measuring Circular Economy strategies through index methods: a critical analysis

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Measuring Circular Economy strategies through index methods: a critical analysis

Abstract

In the last years, the circular economy (CE) paradigm is being widely explored by researchers and institutions as a possible path to increase the sustainability of our economic system. Reuse, repair and recycling are becoming crucial activities in many sectors. At the same time, companies are showing an increasing interest for this new economic model. However, the state of the art shows that a deep research on CE assessment and indicators is still lacking, in particular on the micro level. This work tries to fill this gap, first analyzing the current literature on CE assessment, then proposing a reference framework for the monitoring phase of a CE strategy. Finally, the main existing environmental assessment methodologies based on indexes are analyzed according to their suitability to evaluate the circularity of a system. A systematic approach for the choice of the adequate methodology is also provided, highlighting the main critical steps in the assessment of a CE strategy. Further research could be focused either on the extension of this approach to include other assessment methods, and on the validation of this proposal in a case study.

Keywords: Circular Economy; assessment; index methods; micro level; environmental impact.

Introduction

A worldwide trend is leading the international community to explore possible paths for the transition from Linear to Circular Economy (CE) business models. In linear economy, an industrial process is characterized by a unidirectional material flow, with raw materials that are transformed into a final product and finally disposable waste. In the new concept of CE, recovery and valorization of waste allow reusing materials back into the supply chain, finally decoupling the economic growth from environmental losses (Ghisellini et al., 2016). This issue is confirmed by recent EU documents, which focus on encouraging recycling and recovery strategies all along the lifecycle of a product (EEA, 2016). A growing interest can be also outlined in the US policy looking at the waste management field: the reduction of waste and increase of efficient and sustainable use of resources is defined as a strategic goal, leading from the concept of waste management to a wider material management framework (Heck, 2006). Furthermore, also emerging economies – such as China - are developing guidelines to support CE strategy by focusing on the national level (Geng et al., 2012). Although the research about CE has its major contributions only in the last decade, several reviews and general frameworks can be found in the scientific literature. Nevertheless, few studies are focusing on how to measure effectively the “circularity” level of a product, a supply chain or a service. The state of the art about CE shows that, while the concept of CE is being widely explored and several case studies analyze its application in different contexts, the definition of tools and criteria for measuring the level of circularity of products, companies or regions is still lacking (Haas et al., 2015). Several authors shed a light on this gap, pointing out the importance of well-designed and effective indicators in the transition from a linear to a circular economy (Di Maio and Rem, 2015; Geng et al., 2013; Genovese et al., 2015; Guogang and Chen, 2011; Moriguchi, 2007; Pintér, 2006; Zhijun and Nailing, 2007). The European Environmental Agency identifies the main policy questions concerning CE related to five areas, in a lifecycle perspective: material input, eco-design, production, consumption and waste recycling (EEA, 2016). Recently, Ghisellini et al. (2016) found out that only a few studies (i.e. 10 out of the 155 reviewed) focused on the design or discussion of indicators for the assessment of CE strategies, despite the strategic importance of evaluation and monitoring tools, highlighting a gap in the CE research. This study aims to fill this gap, critically analyzing and comparing the global effectiveness of the most widespread environmental assessment methodologies based on quantitative indicators in measuring the actual level of application of CE strategies to companies, products or services. The reminder of the paper is structured as follows: a reference framework for the monitoring process of CE strategies is proposed in Section 1, while a classification proposal of index-based methodologies for assessing environmental impacts of a CE strategy is in Section 2. Section 3 provides the state of the art about the measurement of CE performances, and a critical analysis is reported in Section 4. Section 5 presents a discussion about the main findings with a systematic approach to guide the choice of a proper methodology, while conclusions are summarized in Section 6.

1. The Circular economy paradigm: a reference framework for the monitoring process

Grounding its roots in the consolidated concepts of environmental science and sustainable development (Sauvé et al., 2015), the CE paradigm introduces a new perspective to look at the industrial ecosystem, where the economic growth is decoupled from resource consumption and pollutant emissions as end-of-life materials and products are conceived as resources rather than waste. This means closing the loops of materials, reducing the need for raw materials and the waste disposal. In order to define an effective measurement process of the CE paradigm adoption, the main issues regarding this new model must be evaluated and analyzed. By analyzing different documents in literature, a four-levels framework has been introduced for supporting measurement of the CE paradigm adoption; the four outlined levels are the **processes** to monitor, the **actions** involved, the **requirements** to be measured, and, finally the i**mplementation levels** of the CE paradigm. The framework is depicted in Figure 1.

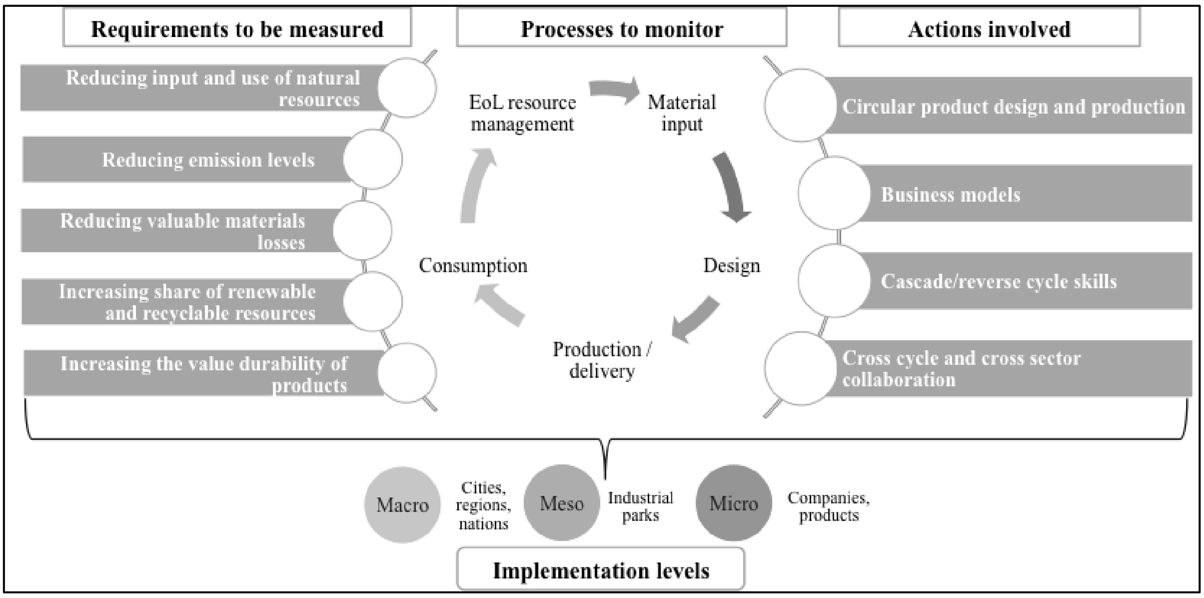


Figure 1: The Circular Economy framework.

Starting from the first category, the CE paradigm usually involves five main phases: the material input, the design, the production, the consumption, and, finally, the end-of-life (EoL) resource management, which provides inputs for the first phase in a closed loop logic. These phases represent, in the proposed framework, the processes, whose performances must be measured to evaluate how circular is the overall system in analysis. Actions involved have been deducted by a recent report proposed by Ellen MacArthur Foundation (2013), which has defined basic "building blocks" for supporting the adoption of CE paradigm; four categories of actions have been introduced in the framework:

a) **Circular product design and production**: several actions can be included in this category starting from eco-design methods oriented to facilitate product re-use, refurbishment and recycling, the design of products and processes with less hazardous substances;
b) **Business models**: this category mainly includes the diffusion of new models, such as product–service systems rather than product ownership, or collaborative consumption tools based on a wider diffusion of consumer-to-consumer channels;
c) **Cascade/reverse skills:** interventions basically focus on supporting closed loop cycles, e.g. with innovative technologies for high-quality recycling, which allows avoiding down-cycling, or for cascading use of materials where high-quality recycling is not feasible. A more efficient support to secondary raw materials market will be also essential;
d) **Cross cycle and cross sector collaboration:** actions in this category focus on building collaboration across the new value chain, also through the involvement of new actors, preventing by-products to become waste trough an effective industrial symbiosis.

Moreover, policy intervention through economic incentives and regulatory frameworks, as well as a rise of awareness and skills, is required to guarantee favorable system conditions for this transition (EEA, 2016; Ellen MacArthur Foundation, 2015a). Next, the requirements to be measured have been deducted from a recent European report (EEA, 2016); five main categories have been introduced:

a) **Reducing input and use of natural resources**: the main aim is to reduce the erosion of the natural ecosystem currently caused by linear models. In brief, the objective is to deliver more value from fewer materials. The direct consequence is also the *preservation of natural resources*, with an efficient use of raw materials, water and energy;
b) **Reducing emission levels:** this refers to direct as well as indirect emissions;
c) **Reducing valuable materials losses**: the implementation of closed loop models to recover and recycle products and materials through reverse flows allows preventing waste production, minimizing incineration and landfilling and decreasing energy and material losses;
d) **Increasing share of renewable and recyclable resources***:* the aim is to cut emissions throughout the full material cycle through the use of less raw materials and more sustainable sourcing; another issue is to reach overall less pollution through cleaner material cycles;
e) **Increasing the value durability of products**: this goal can be reached through the extension of products' lifetime, the adoption of new business models based on use-oriented services (e.g. product leasing and pooling), the re-using of products as well as components, and a high diffusion of material recycling.

Finally, three main **fields of intervention** of the CE paradigm are currently outlined (Ghisellini et al., 2016): the *micro level* - referring to single companies or customers-, *the meso level* - meaning eco-industrial parks- and the *macro level* - from cities to nations.

2. A taxonomy of index-based methodologies for measuring the adoption of CE paradigm

One important question to answer in the research about CE is whether existing methodologies can be successfully used to measure the environmental effectiveness of CE strategies according to the system to be measured. With this purpose, several index-based methodologies have been selected to evaluate their "capability" to measure the adoption of CE paradigm. The selection was made studying recent articles reviewing the main environmental assessment methodologies (Angelakoglou and Gaidajis, 2015; Čuček et al., 2012; Galli et al., 2012; Gasparatos et al., 2008;

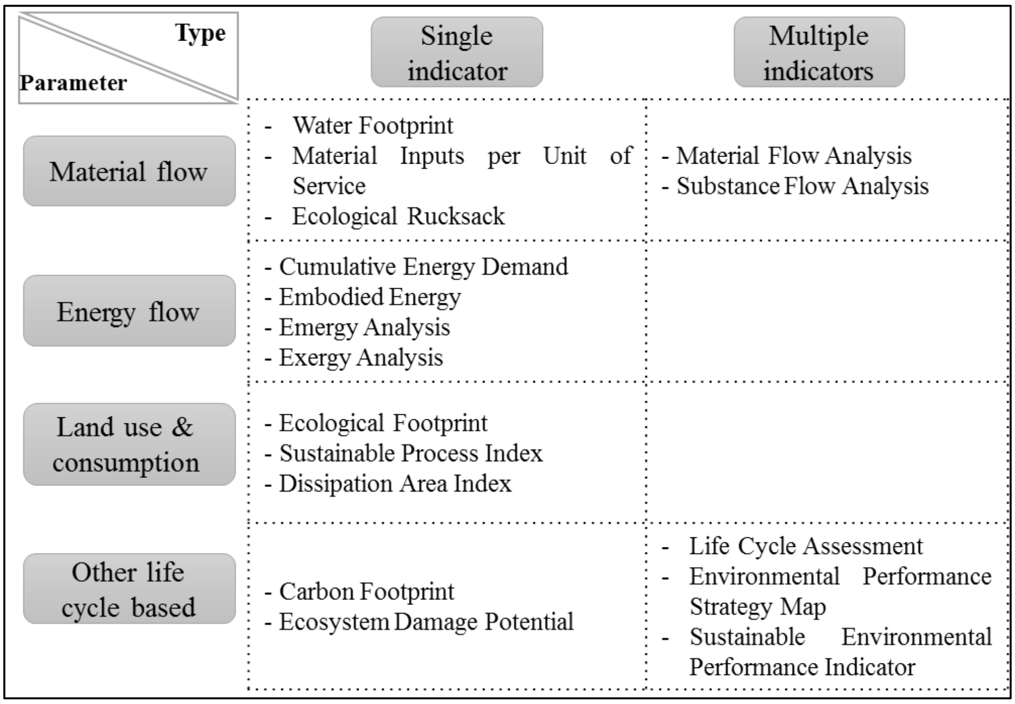
Herva et al., 2011; Ness et al., 2007). The following criteria have been followed to choose the fitting methodologies among the many available:

- the methodology is based on a life cycle approach;
- the methodology adopt a standardized approach or it is commonly used in the industrial or service sectors, recognized as effective for measuring environmental impact in different reviews. As an example, in the footprint family, only three (Ecological footprint, Water footprint and Carbon footprint) are standardized; moreover, several different footprints are presented by Čuček et al. (2012), but some of them (e.g. Nitrogen footprint, Emission footprint) are not included in any other work analyzed.

The taxonomy proposed is based on two factors:

- *the index-based method typology*: the methodology can be based on a single synthetic indicator or on a set of multiple indicators usually divided in several categories;
- *the parameter(s) to be measured:* four categories have been introduced such as material and energy flow, land use and consumption, and other life cycle based.

The selected techniques are summarized in Figure 2. Following, a brief description of these methodologies and their potential contribution to effectively measure the CE adoption based on the framework proposed in Section 1 is presented.



Type Parameter	Single indicator	Multiple indicators
Material flow	- Water Footprint - Material Inputs per Unit of Service - Ecological Rucksack	- Material Flow Analysis - Substance Flow Analysis
Energy flow	- Cumulative Energy Demand - Embodied Energy - Emergy Analysis - Exergy Analysis	
Land use & consumption	- Ecological Footprint - Sustainable Process Index - Dissipation Area Index	
Other life cycle based	- Carbon Footprint - Ecosystem Damage Potential	- Life Cycle Assessment - Environmental Performance Strategy Map - Sustainable Environmental Performance Indicator

Figure 2: The proposed taxonomy of index-based methodologies

2.1. Index-based methods focused on material flows

Three techniques have been included in the single indicator category: *Water footprint (WF)*, *Material Inputs Per unit of Service (MIPS)* and *Ecological Rucksack (ER)*. The WF is an index method applied to measure single-impact information about a product/service, developed in 2002 by Hoekstra and Hung (2002). It indicates potential environmental impacts related to fresh water on the base of a life cycle approach, identifying the total volume of water consumed or polluted over the full supply chain of the good/service, considering also the current state of the hydrological basin from which the water is provided. WF is highly context-dependent, as the availability of fresh water depends on space and time. Standards for the WF calculation are recent: in addition to the Water Footprint Network standard (Hoekstra et al., 2011), the ISO 14046 has been released in 2014

(International Organization for Standardization 14046, 2014). The adoption of WF could support the identification of the most impacting stages of the life cycle by focusing on water use efficiency and management. It can be useful for supporting the decision-making and communication processes carried out by governments, NGOs, and companies: therefore, it can be applied at all the three levels of intervention defined in the framework proposed in section 1. On the other hand, it does not consider any other impact category: so, its adoption is effective only for processes where water consumption and pollution are major issues. The MIPS method allows to measure impacts related to a specific type of material flow (i.e. the material input of a product, a service or a process) based on a cradle-to-cradle approach (Spangenberg et al., 1999): it estimates all the material inputs required for the production, distribution, use, redistribution and disposal of a product/service. Inputs from all the lifecycle phases are referred to the unit of product/service provided. It is usually applied by companies to outline potential savings and environmental impacts, but it can be also applied at more strategic levels. Similarly, the ER is defined as the total sum of material inputs minus the mass of the product: it allows outlining the impact exerted by the goods on the environment. Both methodologies are used to measure the material intensity (i.e. weight of the material in terms of kilograms) requested by a product/service; some authors (Angelakoglou and Gaidajis, 2015; Herva et al., 2011; Spangenberg et al., 1999) suggest to adopt the MIPS calculation when a comparative analysis is requested. These last two methods can be easily applied at the micro level. Two techniques based on multiple indicators have been also included, that is *Material Flow Analysis (MFA)* and *Substance Flow Analysis (SFA).* The MFA has been defined as “a systematic assessment of the flows and stocks of materials within a system defined in space and time” (Brunner and Rechberger, 2004). It is also used by the System of Environmental-Economic Accounting, which provides internationally comparable statistics on the environment and their relationship with the economy. Its main limitations lie in the fact that not all the environmental impacts are explicitly accounted; in addition, the MFA provides information about the quantity of materials used, not about their “quality”: as an example, secondary flows in a closed-loop economy can be characterized by a lower quality than primary flows, thus resulting in down-cycling (Moriguchi, 2007). For this reason, the use of MFA alone is not sufficient for a complete environmental assessment analysis (Brunner and Rechberger, 2004). The SFA method focuses on estimating the flows and stocks of substances involving a risk for environment and health, through a system defined in space and time (Huang et al., 2012). The rationale is to identify the most hazardous flows in order to elaborate strategies to reduce the related environmental burdens. Unlike the MFA, it focuses on single substances rather than materials and goods, thus the data collection process requires usually more effort than in MFA. On the other hand, SFA can be more effective to identify harmful flows of hazardous substances, as well as to manage strategies for recycling and resource conservation, even though it cannot quantify the related environmental impacts (Brunner, 2012). Both for SFA and MFA, their high flexibility allows to easily apply them at the macro, meso and micro level (Herva et al., 2011).

Finally, analyzing methods focused on material flows from a CE perspective, they could be powerful to assess resource depletion and material losses, as well as the quantity of renewable materials used in a process. On the other hand, they do not give any information about the impacts related to those material flows, nor about the emissions caused.

2.2. Index-based methods focused on energy flows

These methodologies are mainly focused on energy usage, which is an important feature in the CE as defined previously. All methods included in this category are based on a single synthetic indicator; four methods have been evaluated, that is *Cumulative Energy Demand (CED), Embodied Energy (EE), EMergy Analysis (EMA), EXergy analysis (EXA)*. The CED is defined as the total amount of energy required to produce a product (or a service) estimated over its whole life cycle: thus, it includes the energy necessary starting from the extraction of raw materials, to manufacturing processes and final disposal (Huijbregts et al., 2006). It is a lifecycle-based single indicator effectively aggregating all forms of energy use. Several approaches exist for CED calculation: no common standardized methodologies are available yet, although some researchers are trying to fill this gap (Frischknecht et al., 2015) together with practitioners, e.g. the Association of German engineers has proposed some guidelines, the so called VDI 4600 (Verein Deutscher Ingenieure, 2012). The EE index is calculated as the sum of all direct and indirect energy flows necessary to produce a product or a service (Brown and Herendeen, 1996); it is a measure of how much energy is incorporated in the product itself, thus this is a reliable tool to identify inefficiencies due to the energy use (Angelakoglou and Gaidajis, 2015). It is usually indicated as the quantity of non-renewable energy per unit of weight (usually in MJ/kg); renewable energy sources can be included as well (Herendeen, 2004). Both methods fit better for the micro level of intervention, but they have been also applied at the macro level (Nawaz and Tiwari, 2006).

Differently from the previous methods, the EMA focuses on estimating the total quantity of energy - direct and indirect- required to produce a product or service estimated in units of only one type of energy, usually the solar energy. Emergy is commonly expressed in solar emergy Joules (seJ); the so called solar transformity factors (expressed in seJ/J) are used to perform such estimations. Thus, this method allows assessing the quantity as well as the quality of the energy required for producing a product/service, providing mostly information about the efficiency of energy use. Nevertheless, one critical activity could be to obtain all the necessary information for the analysis, especially for assessing the transformity factors (Angelakoglou and Gaidajis, 2015; Brown and Ulgiati, 2004; Herva et al., 2011). EXA is based on the estimation of a single indicator defined as “the maximum amount of work which can be produced by a system or a flow of matter or energy as it comes to equilibrium with a reference environment” (Rosen and Dincer, 2001). Like the EMA, exergy is an indicator of energy quality, not only quantity. It can be useful to identify the energy inefficiencies in a process, but also to outline their causes (Rosen et al., 2008). These last two methods have been widely applied to environmental performance at the macro, meso and micro level, although an international common standard is not yet published. Some attempts to define a general methodology to perform an exergy analysis are present in literature, but a standardized procedure is still lacking (Ghannadzadeh et al., 2012). All these methodologies can provide a useful insight on energy efficiency in a process, in some cases giving information about the quality of energy sources. Thus, they can be suitable especially for energy intensive processes, or in general, when a focus on energy efficiency and renewable sources is needed. Nevertheless, they do not include other environmental impacts (e.g. emissions in air, soil and water, material losses, resource depletion).

2.3. Index-based methods focused on land use and consumption

The most widespread methods included in this category are: the *Ecological Footprint* (EF), the *Sustainable Process Index* (SPI) and the *Dissipation area index* (DAI). The EF methodology has been developed in the nineties (Rees, 1992): it is a single based index estimating the biological capacity of the planet consumed by a specific human activity or population. In detail, the EF provides a measure of the total amount of productive land required- including demand for food, crops, timber, energy, space for infrastructure and the area needed to absorb carbon emissions generated. It is expressed in global hectares (gha), a unit of measure accounting the different bio-productivity characterizing different types of land use and countries; thus, estimation of EFs under different conditions are comparable (Galli et al., 2012). Although the EF is a single indicator, it indirectly provides an assessment about the combination of different environmental impacts, such as land-use change, fish consumption, CO_2 emissions. A standardized methodology – defined as Ecological Footprint Standards- was published by the Global Footprint Network (GFN, 2009); an interesting review about its actual estimation in the literature is in Wiedmann and Barrett (2010). The EF method is intuitive and synthetic; thus, it can be used to easily communicate quantitative results obtained at the macro, meso and micro level. Nevertheless, data availability and uncertainty, issues due to the geographic specificity, as well as the need to convert data to area units, could require a huge effort. Similarly to EF, the SPI methods aims to assess the area necessary to support such human activities in all their life cycle: in detail, it measures the total area needed to embed a product/service, in a sustainable way, into the biosphere (Narodoslawsky and Krotscheck, 1995). Its calculation is based on the mass and energy flows estimated in the reference period; thus it is space and time dependent. On one hand, the SPI allows to aggregate material and energy flows and can be used to evaluate the impact of processes, activities or regions. On the other hand, it requires a high availability of regional data – which are usually uncertain in the short period - and its calculation is highly time intensive (Čuček et al., 2012). Finally, the DAI derives from the SPI estimation: it represents the total area needed to absorb the output flows of a specific process. Unlike the EF, the DAI includes the absorption of those substances that do not belong to closed cycles in nature, thus are considered unsustainable (Herva et al., 2011; Narodoslawsky and Krotscheck, 1995).

All the methodologies included in this category aim to measure the human pressure on the biosphere caused by process/product/service through a single index, including implicitly different impacts related to the human activities. This feature could represents an advantage for the results communication process, but it represents a limit when a more comprehensive analysis is required: as an example, these indexes do not provide specific information about each impact category, as results are aggregated. Therefore, these methodologies can fit to compare different CE strategies based on the environmental pressure caused, but they hardly support a deep critical analysis.

2.4. Other life-cycle analysis methods: single and multiple indicator based impact assessment

The last category includes more generalist index methods: two belong to the single indicator category - *Carbon footprint (CF)* and *Ecosystem Damage Potential (EDP)* – and three belong to the multiple indicator one, that is *Life cycle assessment (LCA)*, *Environmental Performance Strategy Map (EPSM)* and *Sustainable Environmental Performance Indicator (SEPI)*. The CF is a well know environmental performance indicator measuring the impact of human activities on global climate, expressed as GreenHouse Gases (GHG) emissions generated by a system. Usually, all GHG contribution (CO_2, CH_4, N_2O, HFCs, PFCs, SF_6) are assessed and expressed as carbon dioxide equivalent (CO_2eq), considering their specific Global Warming Potential (GWP). CF estimation is carried out on a life cycle basis. Several standards have been published to support the CF estimation: the PAS 2050 published by the BSI (British Standards Institution, 2011), the GHG protocol published by the World Resources Institute (WRI and WBCSD, 2011), and finally, the ISO 14067 (International Organization for Standardization 14067, 2013). One of the main strengths of the CF is that it is easy and immediate to understand for non-expert readers: its high communicability has been exploited by companies, organizations as well as policy actors, to illustrate the environmental outcomes of their services or products. Nevertheless, the main limitation is the focus on GHG emissions and global warming potential, which neglects all other impact categories. The EDP has been recently developed by the Swiss Federal Institute of Technology to evaluate the impacts on ecosystem due to land use and transformation. It includes several damage functions and characterization factors for land use types. Linear and non-linear models are used to calculate the damage caused to the species diversity by a process or a product/service (Koellner and Scholz, 2008; Scholz, 2007). Differently from the CF method, the EDP is usually used to communicate results to an expert audience, as its fully comprehension requires high technical skills. Next, the LCA is a well-known multiple indicator method applied since several years in environmental impact assessment at the macro, meso and micro levels. It has been standardized by international guidelines defined in the ISO 14040 family (International Organization for Standardization 14040, 2006). The LCA method is one of the most complete environmental assessment methodologies, as it includes several impact categories related to human health, consequences on ecosystem and on resources. Nevertheless, developing LCA requires an extensive amount of data not often available, thus increasing the uncertainty of obtained results. Moreover, it is time consuming compared to other methodologies, and results communication requires an expert audience. The EPSM is a graphical representation that integrates five footprints (water, carbon, energy, emissions and work environment, which is the number of reported lost days of work per weight unit of product) with a transversal cost-dimension. The objective of the EPSM is to provide a single composed indicator. For each footprint, a maximum target is defined and the value is expressed as a percentage of this target. Results are mapped on a spider diagram, while the cost is considered as the second dimension: it represents the height of the pyramid that has the spider diagram as a base. The volume of the pyramid represents the overall impact and it is called Sustainable Environmental Performance Indicator (SEPI). The main advantage of EPMS is that it combines different footprints in a single indicator, but limited data availability and data uncertainty represent some of the weaknesses of this metric, together with the lack of standardization for some of its components (De Benedetto and Klemeš, 2009).

Finally, it has to be noted that some methods in this category focus on one main impact categories: CF and EDP focus respectively on climate change and damage to ecosystem categories, which indirectly include some of the CE effects on resources flows and energy use, even if their estimation is not explicit. LCA and EPMS estimate directly several impact categories, thus providing environmental assessment from different perspectives and allowing a more accurate evaluation. However, this gain in accuracy corresponds to an increase of data and time needed to run the analysis.

3. State of the art analysis about how to measure the adoption of CE paradigm through index methods

A literature review about index methods used to assess CE strategies has been performed, searching on Web of science, Science direct and Google scholar databases, combining the keywords “circular economy” with “indicators”, “measuring” and “assessment”, among the works published in the last 10 years. In the large amount of articles, only the ones clearly focusing on index based methodologies or sets of indicators to assess the performance of CE strategies were considered. The final total number of articles is equal to 16, summarized as follows and categorized firstly according to the field of interventions of the CE paradigm.

At the macro level**,** several authors adopted the Material Flow Accounting (MFA) or derived indicators to measure the adoption of CE paradigm at the national level. Moriguchi (2007) critically analyzed the adoption of MFA models for measuring circular material flows: experiences from the Japanese national policy have been widely discussed. Haas et al. (2015) proposed a quantitative analysis based on the Economy-Wide MFA (EW-MFA) model to assess the circularity level of the European Union referred to 2005. Several studies adopted index methods defined by legislative and/or technical organizations. Chinese authors have recently published studies based on a specific set of indicators to measure the CE adoption in their country. Geng et al. (2012) discussed benefits and challenges due to the adoption of the so-called “Chinese national CE indicator system”, developed by the National Development and Reform Commission (NDRC). The model includes four main categories: resource output rate, resource consumption rate, integrated resource utilization, and reduction rate in waste discharge. This analysis has been recently integrated in Su et al. (2013) by adding other four categories of indicators, as proposed by the Chinese Ministry of Environmental Protection: material reducing and recycling, economic development, pollution control and administration and management perspectives. The authors validated this approach by comparing the indexes estimated for four pilot cities worldwide. Furthermore, a recent report published by the Ellen MacArthur Foundation (Ellen MacArthur Foundation, 2015b) pointed out four main “circularity areas” to be measured at the national level: resource productivity, circular activities, waste generation and energy and GHG emissions. Guo-gang (2011) and Guogang and Chen (2011) proposed an index method for assessing the adoption of CE at the regional level: the authors introduce also a specific index category to measure social development originated from the adoption of the CE paradigm. Qing et al. (2011) discussed a similar method applied in a Chinese province by adding also other categories of indicators focusing on economic development, environment protection and pollution reduction. These last three studies, proposing a “tailor made” index method with a large (less than 30) number of single indicators, have adopted a multi-criteria model - based on Analytical Hierarchy Process - to prioritize the most critical indicators. Focusing on the city level, Geng et al. (2009) proposed an index method to evaluate the progresses of a CE strategy applied in the city of Dalian (China): the four proposed categories are heavily focused on the waste management process. A similar approach is discussed in Zaman and Lehmann (2013): the so-called “circular city metabolism” measured trough a “zero-waste index”, based on how circular is the waste management process in a city, has been adopted to compare the performance of three cities worldwide.

At the meso level, recent studies proposed different index methods to measure the CE paradigm level of adoption in specific industrial sectors**.** Li and Su (2012) proposed a five categories index method – i.e. defined as economic development, resources exploiting, pollution reducing, ecological efficiency and developmental potential - to assess the circularity level of Chinese chemical enterprises. Wen and Meng (2015) focused on evaluating the contribution of adopting industrial symbiosis to support CE in industrial parks: the authors proposed a Resource Productivity (RP) indicator - derived from the Substance Flow Analysis (SFA) approach - for assessing the CE paradigm level of adoption characterizing the Chinese printed circuit boards industry. Differently, Genovese et al. (2015) adopted a standardized index method - i.e. an hybrid LCA model combining traditional LCA with an environmental input-output analysis - to compare performances of circular production systems in two process industries, i.e. food and chemical. The authors also underlined the need for more relevant environmental indicators to measure the effectiveness of circular models. Recently, Scheepens et al. (2016) applied the LCA Eco-cost and Value Ratio (EVR) model as a single indicator, integrating effectively costs, eco-costs and market value, to assess the level of CE adoption in a regional water recreation park.

At the micro level**,** the Ellen MacArthur Foundation (Ellen MacArthur Foundation, 2015a) recently proposed an index, called Material Circularity Indicator (MCI), to measure how restorative flows are maximized and linear flows minimized, considering also the length and intensity of the product use. The MCI can be adopted both on a product and on a company level; in this latter case, the company MCI is calculated as a weighted sum of MCIs values estimated for all products. Di Maio and Rem (2015) introduced a single index to measure the circularity level of a product, i.e. the Circular Economy Index (CEI) defined as the ratio between the material value obtained from recycled products and the one entering the recycling facility. Park and Chertow (2014) proposed a single indicator characterizing each material defined as Reuse Potential Indicator (RPI), which indicates how much a material is “resource-like” rather than “waste-like” according to the current available technologies. It can serve practitioners as a guide for decision making in the recycling phase.

4. A critical analysis of the scientific literature about measuring CE paradigm trough indicators

Analyzing the scientific literature reported in the previous section, an interesting result can be outlined: about 43% of papers currently adopted multiple index methods ad hoc developed by the authors; on the contrary, only 19% adopted well know index methods, i.e. MFA and LCA. Finally, 38% of studies proposed a single index method for supporting a one-dimension analysis of CE. Furthermore, the most analyzed CE field of intervention is currently the macro level: 56% of analyzed studies focus on the assessment of CE strategies at this level, while 25 % and 19% look at the meso and micro level respectively. Table 1 outlines the literature classification based on the "ability" of each method to measure the five CE requirements presented in framework proposed in section 1.

Table 1: State of the art analysis about CE measurement

			CE requirements				
	#	**Methodology**	Reducing input and use of natural resources	Increasing share of renewable and recyclables resources	Reducing emissions	Reducing valuable material losses	Increasing the value durability of products
Macro	Moriguchi, (2007)	Standardized Indicator set	x	x			
	Haas et al. (2015)	Standardized Indicator set	x	x			
	Geng et al., (2012)	Specific indicators set	x			x	
	Guo-gang, (2011); Guogang and Chen (2011)	Specific indicator set	x	x	x	x	
	Qing et al., (2011)	Specific indicator set	x	x	x	x	
	Geng et al. (2009)	Specific indicator set	x			x	
	Zaman and Lehmann (2013)	Specific single indicator		x		x	
	Su et al. (2013)	Specific indicator set	x	x	x	x	
Meso	Li and Su, 2012	Specific indicator set	x		x	x	
	Genovese et al. (2015)	Standardized Indicator set	x	x	x	x	
	Wen and Meng, (2015)	Specific single indicator	x			x	
	Scheepens et al., (2016)	Specific single indicator					
Micro	Ellen MacArthur Foundation, (2015a)	Specific single indicator	x	x		x	x
	Di Maio and Rem, 2015	Specific single indicator		x			
	Park and Chertow (2014)	Specific single indicator		x			

By focusing on studies on the micro level, all studies adopt not standardized single index methods to measure performances of recycling, reuse and flow circularity. Thus, these indicators are all linked to two particular requirements of CE, i.e. the use of recyclable resources and the input of natural resources. Only the Material Circularity Indicator proposed by the Ellen MacArthur Foundation (Ellen MacArthur Foundation, 2015a) shows an attempt to include in the analysis the loss of materials and the product durability. This last requirement, in particular, is not considered in any other of the studies analyzed, despite its importance in a CE strategy: planned obsolescence represents one of the main obstacles on the way to product durability, especially in electronics (Guiltinan, 2009). Resource use is also the only dimension being considered in all the articles reviewed, probably due to the strong resource-oriented characterization of the CE concept: natural resources' consumption, material losses and the use of renewable resources are requirements considered in several case studies on all the three application levels.

Nonetheless, focusing on one single dimension (i.e. resource use) represents a limitation in the assessment of CE models, leaving other important factors, such as emissions and energy use, out of the analysis (Geng et al., 2012; Moriguchi, 2007). The implementation of CE strategies requires new organizational and logistics models, industrial process and product innovations, often a redefinition of the business paradigm (EEA, 2016). All these changes have to be economically, socially and environmentally sustainable in order to guarantee a successful implementation. This confirms a strong need for further research about more effective CE strategies evaluation, particularly on the micro level. This study focus in particular on the environmental dimension of sustainability, exploring in the following section the possible application of the existing methodologies previously described, for a more complete environmental assessment of CE strategies on the micro level.

5. Discussion

The aim of this study is to evaluate the possibility of filling the current gap in the environmental evaluation of CE strategies ***on the micro level*** with some of the several methodologies already existing and used in the industrial and service sector. Fourteen methodologies for the environmental assessment of products, services or processes, have been presented in Section 2, with their main strengths and weaknesses. Each of them can relate to one or more key requirements of the CE, therefore can be somehow useful to assess some aspects of CE strategies. In this Section, we analyze more in depth their applicability for measuring these requirements and propose a systematic approach to choose the methodology. A first observation is that no one of the selected methodologies is able to monitor the benefits related to all the five requirements. In particular, none of them can capture in a precise and comparable way the capacity of *increasing the value durability* of materials, components and products. This particular benefit of the CE, fostered by policy pressures aiming to discourage planned obsolescence, but also supported through voluntary eco-design strategies, enabled by effective reverse flows management and highly influenced by the customer's behavior, has been neglected so far in the studies considered in all the three levels (see Section 3). Looking at the other CE requirements, among the material flow oriented methodologies, MFA and SFA can give a significant contribution for measuring the input of natural resources, the use of recyclables, the loss of materials and the emissions of pollutants (this latter only in SFA). Nevertheless, as explained in Section 2, the limits of these methods should always be taken into account, starting from the lack of environmental damage quantification and their inability to measure other impact categories. Specifically, MFA does not capture the reduction of emissions, as it only focuses on material flows. WF can be effective when water management is a critical issue in the process analyzed, while it does not fit to other contexts due to its specificity. Finally, MIPS can only quantify the material intensity of a product/service, contributing to the analysis of one CE requirement, while it does not give information about the related emissions, the use of recyclable resources or the loss of materials. The *energy flow based* methods are the most focused on energy use, through quantitative and qualitative analyses. They can surely represent a powerful tool when the focus of the CE strategy in analysis is on energetic flows, as they are among the few tools directly measuring this requirement, but they cannot contribute to the assessment of other dimensions, due to the their narrow application field. In particular, while CED and EE can analyze the quantity of energy used through the lifecycle, EMA and EXA can also give some information about its quality, thus being more effective in the identification of renewable sources. The presented *land use based* methods turned out to include only indirectly some of the CE requirements considered: on one side, the focus on land consumption helps in building more understandable and communicative indexes, but on the other side, it hides the specific benefits of CE converting all the impacts considered in terms of area. Therefore, they are not suitable to measure specific CE requirements, but can rather be used to compare different scenarios and draw generic conclusions about their efficacy. In particular, EF indirectly considers in the calculation of the area needed the consumption of natural resources and the emissions (and waste) generated in the process. Next to materials and emissions, the SPI/DAI also considers the energy flows. Finally, *life-cycle based* methods can support CE assessment in different cases. With exception for EDP, which can only give an indirect evaluation of the impacts related to natural resources consumption (in this case referred to land use), the other tools directly account for one or more of the CE dimensions analyzed. CF and EPMS mostly support the analysis of emissions, focusing on GHG and indirectly accounting for natural resource consumption and energy use. LCA seems to be the most complete of the methodologies here considered, thanks to the variety of indicators available and to the deep detail that the analysis can reach. Nevertheless, its well-known criticalities (e.g. data availability and uncertainty, time intensiveness, ease of understanding for non-practitioners) can eventually represent a barrier to its use. Table 2 summarizes the potentialities of each methodology to assess CE according to its main features.

Table 2: Environmental assessment methodologies and CE requirements

	CE requirements				
Methodology	Reducing input and use of natural resources	Increasing share of renewable and recyclables resources	Reducing emissions	Reducing valuable material losses	Increasing the value durability of products
LCA	Direct quantification	Indirect quantification	Direct quantification	Direct quantification	
SFA	Direct quantification	Direct quantification	Direct quantification (hazardous substances flows)	Direct quantification	
MFA	Direct quantification	Direct quantification		Direct quantification	
WF	Direct quantification (water)		Direct quantification (pollutants in water)	Direct quantification (water)	
CF	Indirect quantification	Indirect quantification	Direct quantification (GHG)		
EPMS/SEPI	Indirect quantification	Indirect quantification	Direct quantification (GHG)		
SPI/DAI	Indirect quantification	Indirect quantification (energy)	Indirect quantification		

EF	Indirect quantification		Indirect quantification		
MIPS	Direct quantification (material intensity)				
EDP	Indirect quantification				
CED		Direct quantification (energy)			
EE		Direct quantification (energy)			
EMA		Direct quantification (energy quantity and quality)			
EXA		Direct quantification (energy quantity and quality)			

By analyzing the *input of natural resources*, this issue can be captured - directly or indirectly- by most of the analyzed methodologies: only methods focused on energy analysis do not consider this impact at all, but on the other side, they are the best tool to capture energy use from fossil and *renewable sources*. In particular, EMA and EXA can give information not only on energy quantity, but also on its quality, and this feature can be a valuable contribution to the evaluation of CE strategies, given the importance of sustainable energy sourcing and use. *Material losses* can be better highlighted through the material flow based tools, especially MFA and SFA, which can measure the use of *recyclable resources* as well. This CE benefit is also indirectly accounted by other tools, such as EPMS, LCA and CF. Finally, LCA seems to be also the most effective methodology for assessing the *emissions* of pollutants, thanks to the different indicators available to calculate impacts. Other tools partially include some emissions in the analysis: CF and EPMS consider GHG, WF captures emissions in water and SFA describes the flow of pollutants, while EF indirectly includes this impact as the area required to absorb the emissions.

Another issue to be analyzed is the capability of each method to account directly or indirectly for the impacts considered. One advantage of a CE requirement direct measurement is the detail of the analysis: direct quantification of the impacts gives precise information and can thus support improvements and decision making focused on that particular requirement. On the other hand, the methodologies considered in this study that account indirectly for some of the impacts related to the CE requirements are synthetic indexes that can easily enable comparisons between two or more alternatives, thus can perform better in results communication and, in general, in a higher level decision making. As an example, an MFA can be successfully used to track the flow of specific materials in a process and highlight material inefficiencies, helping to identify in detail material losses, resource consumption and use of recyclables. By contrast, EF does not explicitly describe the performance of a system according to some requirement of the CE, as it focuses on land consumption, but thanks to its conciseness, it can be effective for the comparison of different alternatives, including indirect impacts due to resource and land management.

By integrating all these issues, a guideline to support both researchers and practitioners in evaluating index methods to be applied for measuring quantitatively the effectiveness of a CE strategy at the micro level has been designed: the flow diagram is in Figure 3. The process should start with the identification of the system to analyze and the main process(es) to monitor. Thus, the assessment could be focused on single process, on multiple processes or on the whole supply chain, according to the scope and depth of the analysis (e.g. to assess a zero waste strategy, a focus on EOL management could be effective) but also the company strategy in adopting the CE paradigm. In the second step, activities to be implemented that are supposed to have an impact on the performance of the system, in terms of CE requirements, should be identified. As an example, in a CE strategy based on the implementation of a product-service system aiming at reducing the material intensity, the use of natural resources and material losses should be monitored among all the requirements to verify its effectiveness. Accordingly, in the third step the focus of the analysis should be made clear, choosing one (or more) CE requirements – e.g. reducing emission levels, increasing share of renewable and recyclables resources - to measure based on the information detailed in the previous phases. As an example, the adoption of a CE strategy in a company could be focused, at first, only on increasing recycling rates (e.g. by providing its waste to a recycling plant) or, in addition, it could be also oriented to re-use its own waste thus reducing its emission levels. At the same time, the necessity to measure these requirements directly or indirectly should be investigated. This last step eventually leads to the choice of an appropriate methodology to assess the circularity of a strategy, based on the classification and on the results provided so far. On one hand, this capability mainly affects the reliability of obtained results as indirect measurement methodology could provide quantitative data not directly related to a specific phenomenon. On the other hand, results are usually characterized by a wider applicability, as they could provide easily comparison analysis.

Finally, it has to be noted that the requirement “increasing the value durability of products”, introduced previously in the proposed framework, has not been included in this picture, as it is not captured by any of the methodologies considered. For further developments, this systematic approach for guiding the assessment of a CE strategy could be enriched extending the analysis to other kinds of methodologies (e.g. sets of indicators) or to other application levels (i.e. meso and macro).

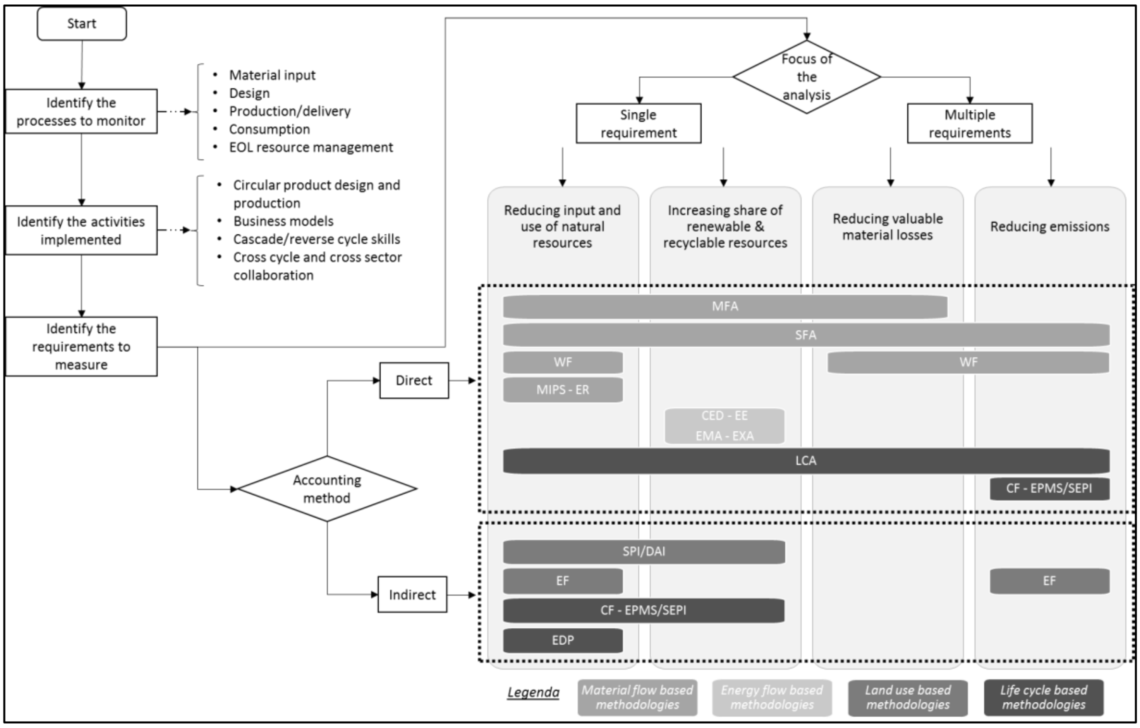


Figure 3: Critical steps in the assessment of a CE strategy

6. Conclusions

Recent reviews about CE show that, despite the growing interest of researchers and practitioners towards the CE paradigm, research about indicators and methodologies for measuring the application level of CE strategies is still in its earliest phase, particularly on the micro level. This paper tries to fill this gap, firstly proposing a four-levels framework to support the assessment phase, which highlights the processes to monitor, the actions involved, the requirements to satisfy and the possible application levels of a CE strategy. Then, the existing methodologies currently adopted to measure the environmental impacts in the industrial and service sectors have been reviewed and classified by outlying their potential adoption for measuring quantitatively the "compliance" with the CE paradigm. After a state of the art analysis about the assessment of CE strategies, which confirmed a lack of standardized methods especially in the micro level, the presented methodologies have been analyzed with reference to their possible application to capture the five CE requirements previously described. Finally, a systematic approach to guide the choice of a possible methodology for CE assessment has been presented. Further developments can be focused, on one side, on the extension of this approach to include other assessment methods (e.g. indicators sets, brand new CE indicators), on the other, to validate this proposal in a case study.

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