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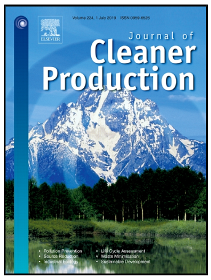

Circular Economy performance assessment methods: a systematic literature review

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Circular Economy performance assessment methods: a systematic literature review

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Abstract

The depletion of resources and the downgrading of the environment, driven by globalization and consumerism phenomena, is worldwide pushing the interest on the Circular Economy (CE) concept. Supposed to substitute the end-of-life notion with restoration and closed-loop product lifecycles, CE wants to eliminate wastes, retain the value embedded into products and materials, foster the use of renewable energies and eliminate toxic chemicals. However, the measurement and assessment of circularity performances are not yet a common practice in companies. To this aim, the paper wants to detect, through a systematic literature review, which are the existing CE performance assessment methods proposed in literature and, based on key findings, develop a positioning framework for measuring and assessing the circularity degree of a company.

Keywords: Circular Economy; performance measurement; systematic literature review; assessment methodology

Acronyms

AHP	Analytic Hierarchic Process	KPI	Key Performance Indicator
ANP	Analytic Network Process	LBM	Longevity Based Method
BoL	Beginning of Life	LCA	Life Cycle Assessment
BM	Business Model	LCI	Life Cycle Inventory
BSC	Balanced Score Card	LCIA	Life Cycle Impact Assessment
BWPE	BIM-based Whole-life Performance Estimator	LCSA	Life Cycle Sustainability Assessment
CE	Circular Economy	M	Material
CPI	Circular economy Performance Indicator	MCA	Material Cost Analysis,
CSF	Critical Success Factors	MCDM	Multi Criteria Decision Methods
CSR/P	Corporate Social Responsibility/Performance	MFA	Material Flow Analysis
CEENE	Cumulative Exergy Extraction from the Natural Environment	MFCA	Material Flow Cost Accounting
DEA	Data Envelopment Analysis,	MoL	Middle of Life
DMU	Decision-Making Units	MADM	Multiple-Attribute Decision-Making
DES	Discrete Event Simulation	MSW	Municipal Solid Wastes
D&D	Design and Development	P	Pollution
DfD	Design for Disassembly	PM	Process Modelling
DfEoL	Design for End-of-Life	PF	Productivity Factor

DfX	Design for X	REA	Real Estate Appraisal
DMI	Direct Material Input	RRBR	Recycling and Reuse Benefit Ratio
DMC	Domestic Material Consumption	RM	Regression Model,
E	Energy	SA	Sensitivity Analysis
Em	Emergy	SCBM	Sustainable Condition-Based Maintenance
EoL	End of Life	SNA	Social Network Analysis
EPI	Environmental Performance Indicators	SIC	Social Impact Coefficient
Ex	Exergy approach	SPA	Sustainable Performance Assessment
ELCA	Exergetic Life Cycle Assessment	SPD	Sustainable Product Development
FA	Factor Analysis	SPA	Sustainable Performance Assessment
GL	Guidelines	SSC	Sustainable Supply Chains
GSC	Green Supply Chains	TBL	Triple Bottom Line
IELR	Improved Environmental Loading Ratio	UEVE	Unit Emergy Value of Economic output
I-O	Input-Output	WEEE	Waste from Electrical and Electronic Equipment

1. Introduction

In 2005, Ellen MacArthur became the fastest solo sailor to circumnavigate the globe. This experience led to the conception and birth of the Circular Economy (CE) concept. She had to prepare herself with *'the absolute minimum of resources in order to be as light, hence as fast, as possible. At sea, what you have is all you have, stopping the route to restock is not an option and careful resource management can be a matter of life or death – running out of energy to power the autopilot means you can be upside down in seconds. My boat was my world, I was constantly aware of its supplies limits and when I stepped back ashore, I began to see that our world was not any different. I had become acutely aware of the true meaning of word 'finite', and when I applied it to resources in the global economy, I realised there were some big challenges ahead'* (The Ellen MacArthur Foundation, n.d.). Today, after more than ten years of investigations, CE is a widespread concept in literature (Winans et al., 2017), involving also companies and policy-makers (Suárez-Eiroa et al., 2019) and impelling the redaction of legislative directions mainly in Europe (EC, 2008) and China (CCICED, 2008). It attempts to overwhelm and leave behind the traditional linear economy based on taking virgin materials from nature and making products to be either consumed or disposed of. CE can be defined as an industrial system that is restorative or regenerative. Its intention is to close the loop of the linear product lifecycle, substituting the end-of-life concept with restoration (The Ellen MacArthur Foundation, 2013). This can be achieved through a superior design of the system to be delivered and of the related Business Model (BM), with the aim of removing wastes and retaining as much value as possible from the products and materials involved (Kirchherr et al., 2017), also fostering the use of renewable energies and the elimination of toxic chemicals. Under the circular perspective, the management of systems becomes more complex. As specified by Ellen MacArthur in 2005, resources are considered scarce and limited and restock is not possible in an infinite way. Indeed, her boat, a finite and limited system, can be compared to the world: both need a careful resource management to be able to pursue sustainability along the time. As well, in the industrial domain, in order to effectively implement circularity and adequately manage the different resources involved, innovative BMs and design practices, coupled with reverse logistic and digital technologies adoption, are needed.

However, as quoted by the Austrian economist Peter Drucker (2005), in order to be able to manage and improve a system, it is needed to be able to measure it: this also applies to resources in circular systems. So far, as reported in Table 1 in Section 2, in literature a shortage of interest in the CE performance assessment area and a lack of methodologies able to consistently measure and gauge concurrently all the variables involved in a circular system have to be registered.

The aim of this research is to investigate, through a systematic literature review, which are so far the performance assessment methods proposed to measure CE systems and how they can be characterized and classified. Indeed, based on the key findings from the literature, a framework has also been proposed: it provides directions about the dimensions and variables to be considered to develop a holistic methodology for the measurement and assessment of the circularity degree of a given system along its entire lifecycle.

Therefore, the article is structured as following: Section 2 reports the research methodology and criteria used to perform the literature analysis about circular performance assessment. Section 3 provides literature analysis results, in terms of trends and areas of interest of this specific research stream but also of the methods so far proposed. Section 4 is entitled to discuss them, also proposing a theoretical positioning framework for CE performance assessment. Finally, Section 5 concludes the paper providing the main remarks and future activities.

2. Research methodology

CE research is continuously evolving. Especially in the last years, this led both researchers and practitioners to understand how to measure and quantify its impacts in a real context. In order to sum up the results obtained so far and gather interesting details on current findings, a systematic literature review (Brereton et al., 2007; Smart et al., 2017; Software Engineering Group, 2007) on scientific articles published up to the second quarter of 2018 and provided by the most popular academic search engines (i.e. Science Direct and Scopus) has been carried out. The main keywords, “circular economy” and its main synonym “end of life”, were combined with “performance”, “assessment” and “methodology” in a total of six searches, without considering any document type, time and field content limitations. To manage to remain inclusive and to harness the variety in the knowledge base, the relevance criteria were initially guided by the question formulation, i.e. the research scope. Indeed, since the aim of the authors has been to find all the documents proposing circular performance assessment methodologies, two initial searches, more extensive than those reported in rows 1 and 4 in Table 1, had to be performed. By removing the quotation sign from "performance assessment", the search results resulted to be significantly different: the documents returned by search engines were consistently more numerous but at the same time resulted to be almost ever out of scope. This is explained by the fact that, taken alone, performance and assessment were too generic concepts. For this reason, authors decided to shrink the focus of the research using more restricting strings. Results of these new queries are reported in Table 1, evidencing that the “end of life” context has been explored more than the “circular economy” one.

Table 1 Searches by keywords

N.	Search	Science Direct	Scopus
1	“circular economy” AND “performance assessment” AND “methodology”	56 (11)	60 (5)
2	“circular economy assessment”	9 (6)	11 (4)
3	“circular economy performance”	9 (5)	30 (0)
4	“end of life” AND “performance assessment” AND “methodology”	316 (12)	186 (2)
5	“end of life assessment”	32 (1)	88 (0)
6	“end of life performance”	65 (4)	124 (3)
	TOTAL (total after selection based on the three criteria)	**487 (35)**	**499 (10)**

The numbers in parentheses in the table represent the number of papers progressively selected along the searches carried out for this literature analysis: after detecting and removing redundancies among the results from the two databases, a first selection by title, abstract and keywords analysis, and a second screening by entire manuscript analysis were performed.

In particular, Figure 1 fully explains the research strategy adopted in the systematic literature review (Smart et al., 2017): searches on Science Direct and Scopus databases (using the six strings reported in Table 1) led to 986 results. Moreover, 18 documents were detected through cross-referencing processes and 9 through hand search. Finally, 5 more documents recommended by experts were added to the list. Through the criteria application, the total amount of documents found was reduced to a final set of 45 selected articles that had been deeply analysed. Two authors performed independently the entire process of selection and analysis of the documents to avoid bias of interpretation during the review: results obtained by each of them were compared and then made consistent to each other. This article presents the joint results of this twofold analysis.

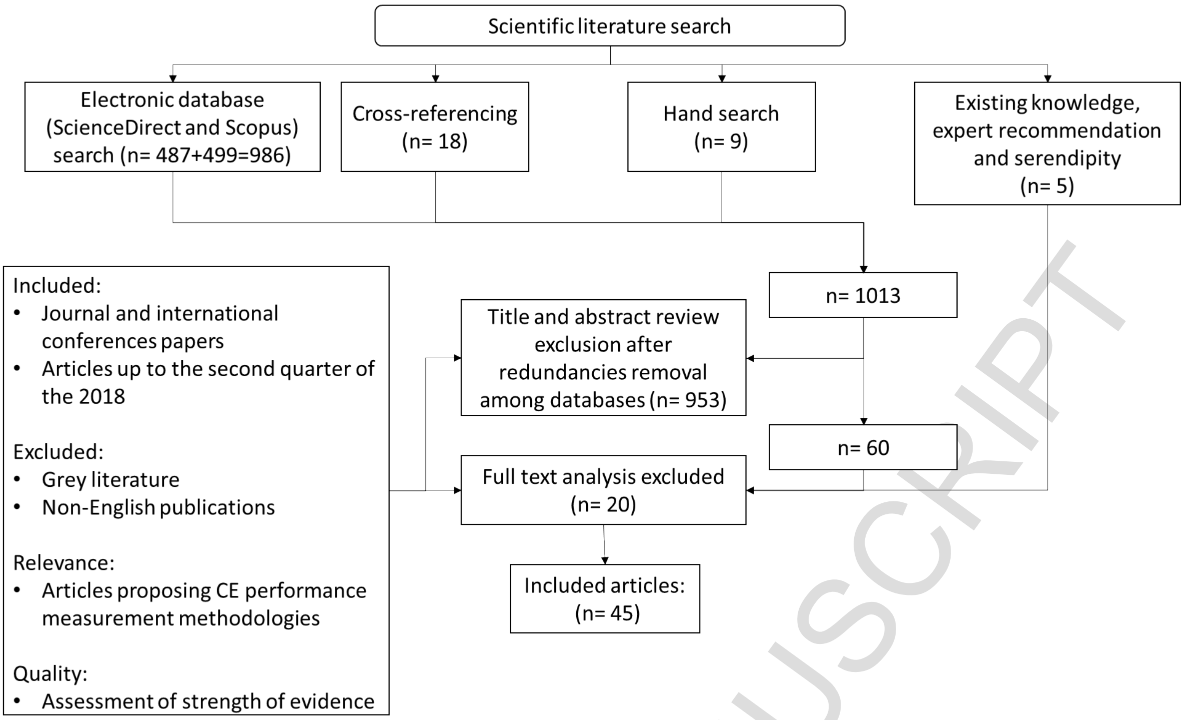

Figure 1 Research strategy (adapted by (Smart et al., 2017))

As shown in section 3, all these papers have been categorized by authors, nation of the authors, keywords, year, title, main content, document type, research type (divided in Theoretical Assessment; Analytical Assessment; Case Studies; Surveys; Action Research; Other), journal, framework/method/approach proposed, assessment methodology used, index proposed, Triple Bottom Line (TBL) perspective (Environmental, Economic, Social), variables analysed (Energy, Material, Pollution), category of industry and Industrial Symbiosis level.

3. Literature review

The selected 45 articles show that the interest on CE-related topics rose from 2015 onward. This trend can be explained by the fact that CE regulations are becoming internationally always more restrictive and relevant, because of resources depletion, consumerism and population growth (*2018 World Manufacturing Forum Report, Recommendations for the Future of Manufacturing*, 2018; The Ellen MacArthur Foundation, 2015). Figure 2 shows how publications are spread along the years, with the greatest part (73,3%) of them published from 2016 onwards.

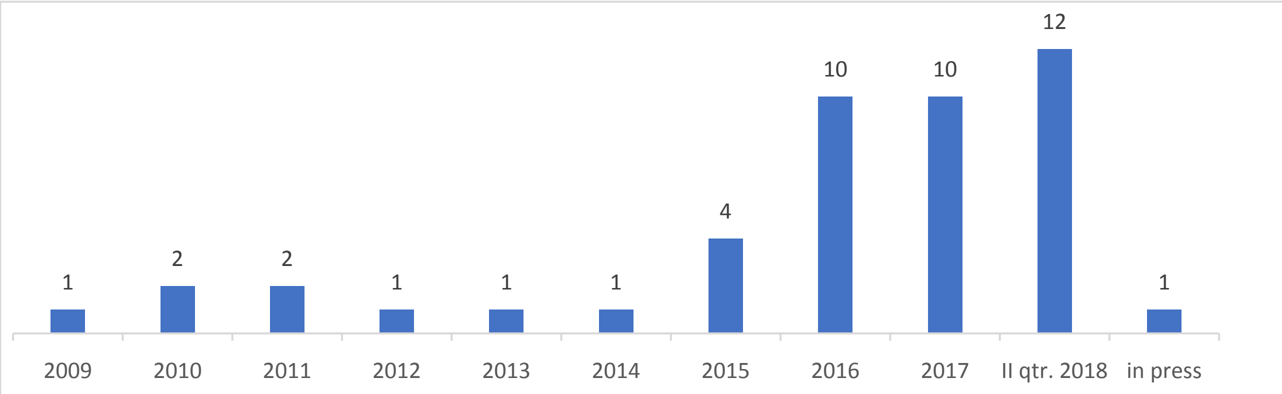

Figure 2. Historical publication trend by year

Considering the type of contribution (see Figure 3), 39 articles were published in scientific journals and 6 in proceedings of scientific international conferences. Two journals are the most impacting in terms of CE-related publications (*Journal of Cleaner Production* and *Resources, Conservation and Recycling)*, with 62,2% of papers considered.

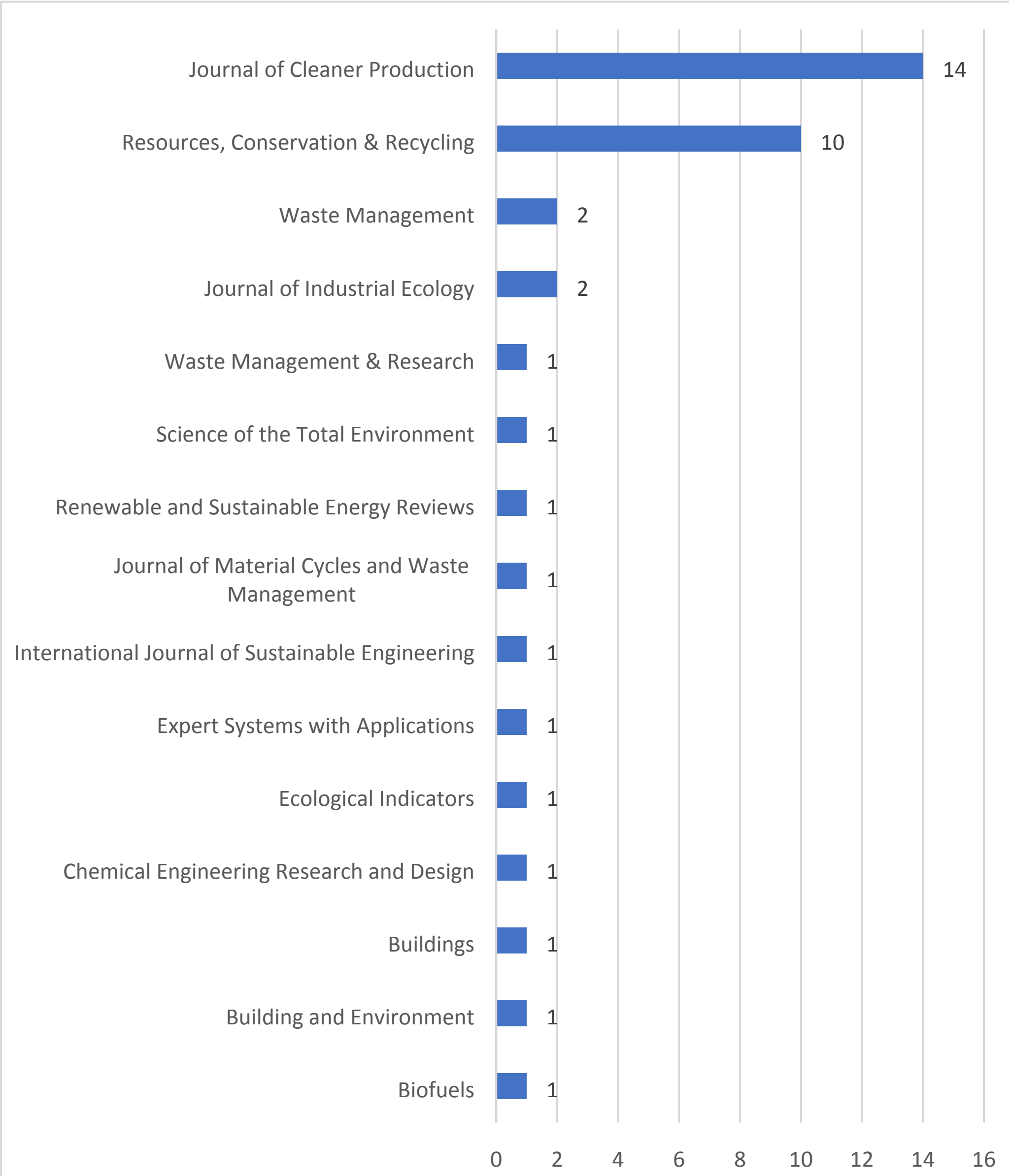

Figure 3. Journals

Considering the nationality of authors, the highest number of contributions come from European countries (57,8%), followed by China. Instead, in terms of first authors' nationality, China is the major contributor (15,5%), followed by Italy (13,3%), France (11,1%), UK (8,9%) and Spain (6,7%) (Figure 4).

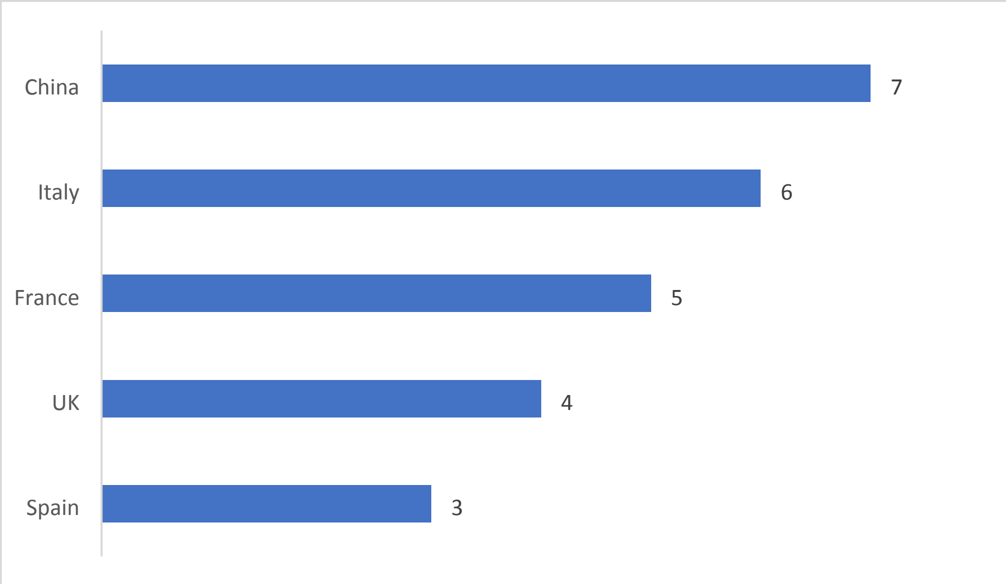

Figure 4. Top five publishing countries

Most of the selected 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. Figure 5 highlights the perspective of analysis. Basing on that, contributions can be divided between those focused on intra-company links (30 contributions) and those focused on inter-company ones (10 contributions). In the first case, the analysis has been 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%).

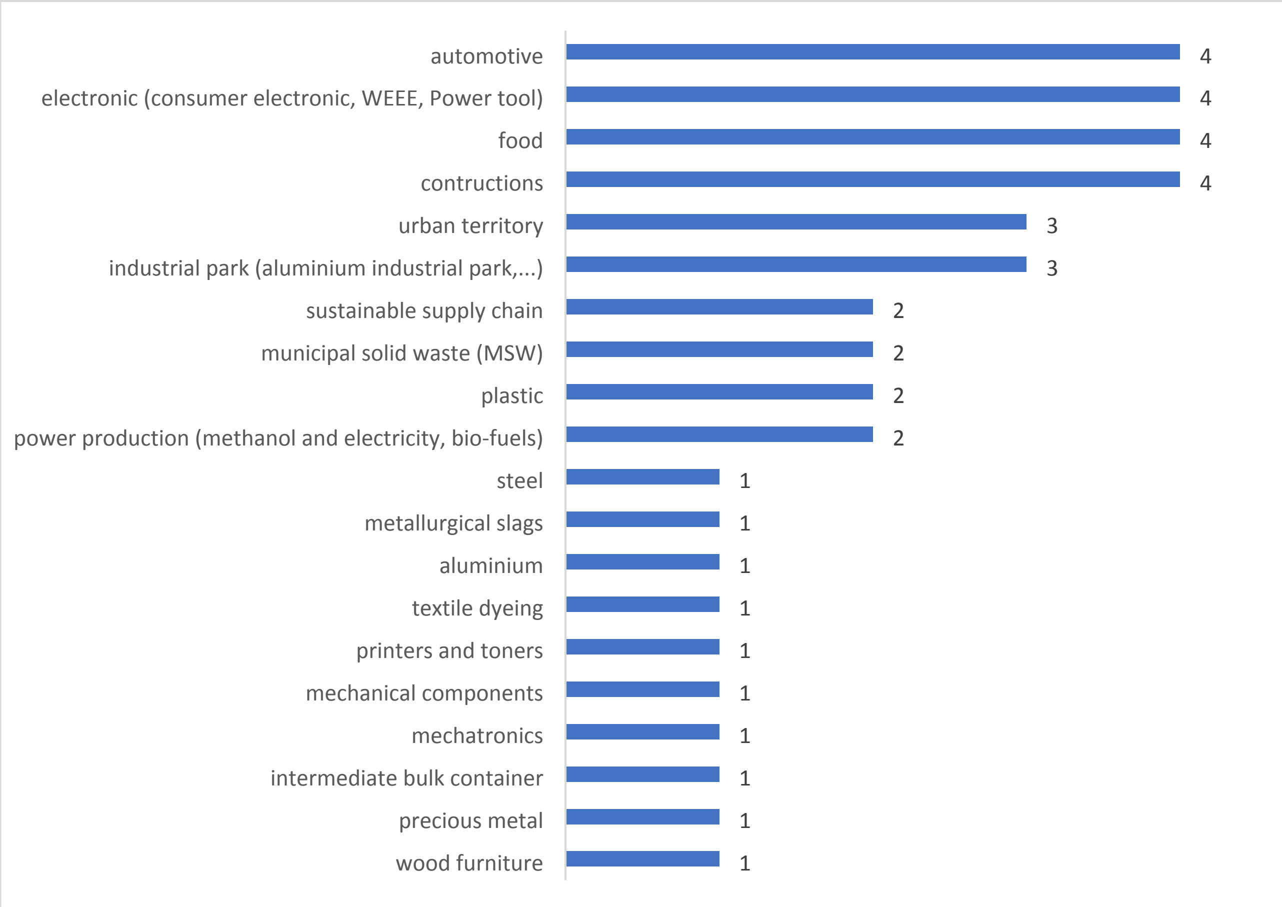

Figure 5. Industries

Figure 6 shows the research approach adopted by papers. Most of authors gave relevance to the industrial side, in order to practically validate the proposed theories. Case study is the most exploited research approach, followed by analytical and theoretical assessments and surveys.

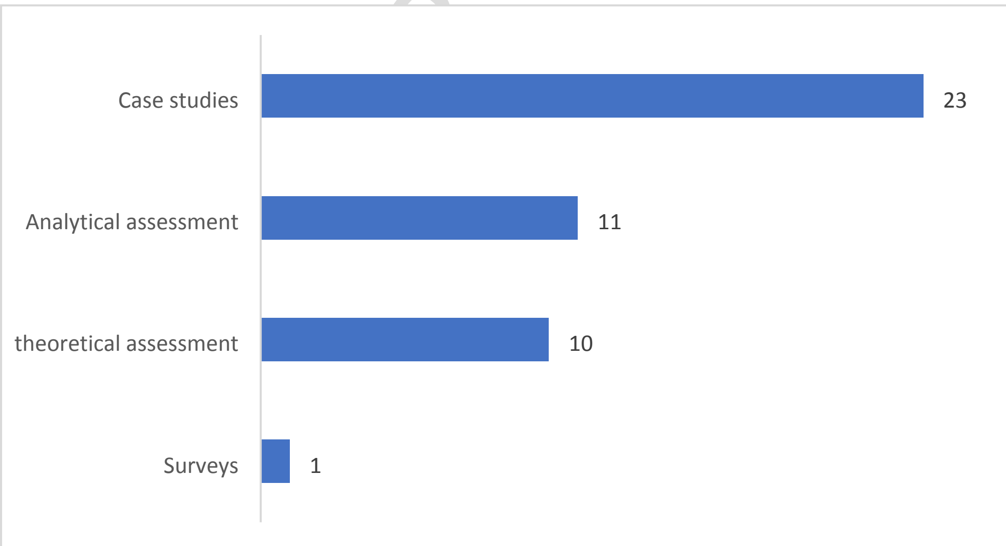

Figure 6. Main typologies of research

3.1 Current state of the art on Circular Economy assessment methods

In general terms, selected papers propose a new framework, method, index or approach, usually starting from a set of already existing ones. However, all of them were focused on measuring just some specific CE-related aspects. Table 2 reports some details about the final set of 45 papers.

Table 2. Performance assessment methods used in the selected CE literature

Authors	Method							
	DEA/ I-O	**DfX/ GL**	**LCA/ LCI/ LCIA**	**MCDM/ fuzzy methods**	**Em, Ex**	**Simulation/ DES**	**MFA/ MCA/ MFCA**	**Other**
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

All the detected approaches (see Figure 7 below), have been analysed in terms of TBL perspective, adopted variables and considered lifecycle stage. However, it must be specified that, within variables, the term "materials" the paper refers to resources constituting the product, while "other resources" are elements (either resources or energy) supporting the production process.

Moreover, dealing with the lifecycle stages, Beginning of Life (BoL) considers both product Design and Development (D&D) and strategic evaluation. Subsequently, Middle of Life (MoL) concerns system operation, service delivery and use phase. Finally, End of Life (EoL) deals with disposal.

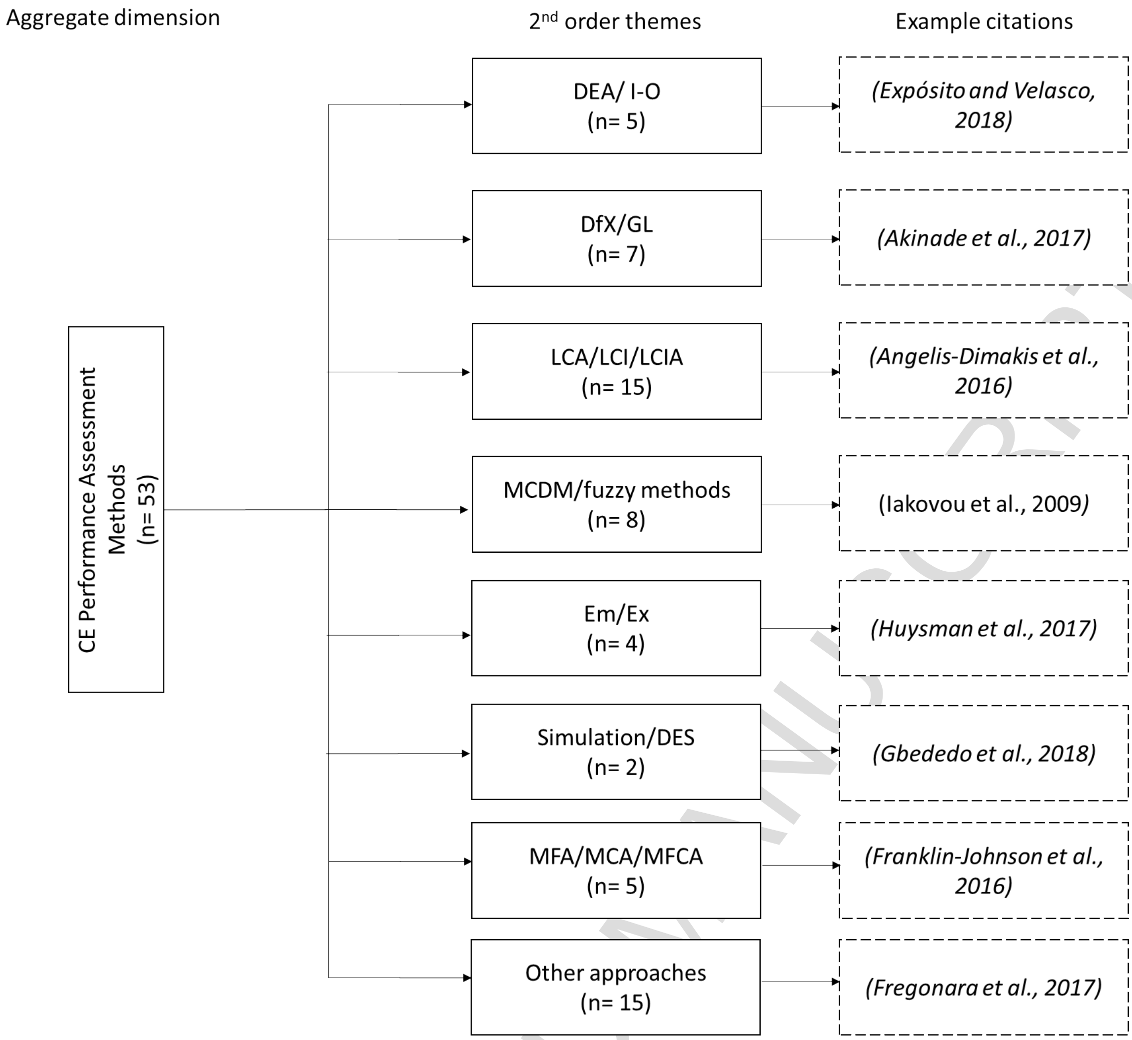

Figure 7. Scheme of CE performance assessment methods

3.1.1 LCA/LCI/LCIA

As reported in Table 2, the most common methodology is Life Cycle Assessment (LCA) (Angelis-Dimakis et al., 2016; Biganzoli et al., 2018; Eastwood and Haapala, 2015; Fregonara et al., 2017; Gbededo et al., 2018; Grimaud et al., 2017; Hadzic et al., 2018; Huysman et al., 2017; Jamali-Zghal et al., 2015; Laso et al., 2016, 2018; Martin et al., 2017; Park et al., 2016; Pauliuk, 2018; Petit et al., 2018). Several examples are available about this topic. (Angelis-Dimakis et al., 2016) developed a LCA-based methodological framework for the eco-efficiency assessment in the textile dyeing industry. (Pauliuk, 2018) proposed a set of CE quantitative indicators, mostly based on Material Flow Analysis (MFA), Material Flow Cost Accounting (MFCA) and LCA, to assess CE performances in organizations. Laso et al. (2016) assessed the treatment and valorisation of wastes combining LCA, LCI and LCIA, subsequently upgraded in a two-step eco-efficiency methodology (Laso et al., 2018). Hadzic et al. (2018) proposed a LCA-based assessment tool of wastes in urban contexts. Similarly, (Martin et al., 2017) used LCA to assess the use of materials and by-products in biofuels. Biganzoli et al. (2018) proposed a LCA-based assessment tool of intermediate bulk containers re-use in CE. Fregonara et al. (2017) combined Real Estate Appraisal, Economic Evaluation of Project Environmental Design, LCA and LCC for developing a decision-making tool supporting designers in the construction industry. (Grimaud et al., 2017) followed the same logic, but providing a decision-support tool combining LCA, MFA and Environmental Technology Verification (ETV). Again, (Eastwood and Haapala, 2015) developed a product sustainability assessment methodology assisting designers, but exploiting LCI, a sub-section of LCA. (Park et al., 2016) proposed an ecological performance assessment framework considering Eco-LCA framework, ReCiPe method and linear programming. (Petit et al., 2018) combined LCA, Corporate Social Responsibility (CSR) and Multiple-Attribute Decision-Making (MADM) for implementing a value chain sustainability assessment framework.

Table 3 shows that, paired together with other methods, LCA was used for measuring materials and other resources (not neglecting energy and pollution), by analysing them at BoL and EoL. In general terms, the perspective is always on environmental and economic aspects.

Table 3. LCA: variables, lifecycle stages and TBL dimensions involved

Authors	Method								Variables				Lifecycle Stage				TBL		
													BoL		MoL	EoL			
	DEA /I-O	DfX / GL	LCA/ LCI/ LCIA	MCDM/fuzzy methods	Em, Ex	Simulation/ DES	MFA/ MCA/ MFCA	Other	E	M	Other Res	P	Product D&D and strategic evaluation	Manufacturing			Env	Econ	Soc
(Petit et al., 2018)			x	x				CSR	x	x	x	x		x	x	x	x	x	x
(Gbededo et al., 2018)			x			x		SPD, SPA	x	x	x	x	x			x	x	x	x
(Angelis-Dimakis et al., 2016)			x							x	x			x	x	x	x	x	
(Pauliuk, 2018)			x				x		x	x	x	x		x	x	x	x	x	
(Laso et al., 2018)			x							x	x			x			x	x	
(Huysman et al., 2017)			x		x				x	x						x	x		
(Biganzoli et al., 2018)			x						x	x	x	x		x	x	x	x		
(Grimaud et al., 2017)		x	x				x			x			x				x	x	x
(Hadzic et al., 2018)			x							x	x	x				x	x	x	x
(Laso et al., 2016)			x						x	x	x	x					x	x	
(Martin et al., 2017)			x							x	x	x				x	x		
(Fregonara et al., 2017)			x					REA	x	x	x	x	x				x	x	
(Eastwood and Haapala, 2015)			x						x	x	x	x	x	x			x	x	x
(Park et al., 2016)	x		x		x				x	x	x	x		x			x	x	x
(Jamali-Zghal et al., 2015)			x		x				x	x				x		x	x		
	1	**1**	**15**	**1**	**3**	**1**	**2**	**3**	**9**	**14**	**11**	**9**	**4**	**8**	**4**	**9**	**14**	**10**	**6**

CSR= Corporate Social Responsibility; SPD= Sustainable Product Development; SPA= Sustainable Performance Assessment; REA= Real Estate Appraisal

3.1.2 Multi-criteria approaches (MCDM) and fuzzy logic

Considering the intrinsic complexity of circular systems, several authors (Iakovou et al., 2009; Kazancoglu et al., 2018; Ng and Martinez Hernandez, 2016; Olugu and Wong, 2012; Petit et al., 2018; Shen et al., 2013; Wibowo and Grandhi, 2017; Xu et al., 2018) adopted multi-criteria approaches and fuzzy logic for assessing them. (Ng and Martinez Hernandez, 2016) proposed a decision-making framework combining multi-criteria analysis and process modelling for assessing CE performances of selected systems. (Shen et al., 2013) used a fuzzy multi-criteria approach for evaluating green supply chain performances. Similarly, (Olugu and Wong, 2012) adopted an expert fuzzy rule-based system for building a closed-loop supply chain performance measurement framework, considering both forward and reverse logistic chains. Wibowo and Grandhi (2017) used a multi-criteria decision-making approach for evaluating recoverability of EoL products through a performance index. Following a similar logic, Xu et al., (2018) applied a capacity-based Multi-Criteria Decision Making (MCDM) approach to Wastes from Electronic and Electrical Equipment (WEEE) recycling. Iakovou et al. (2009) created a methodological framework for EoL management of electronic products, by ranking embedded components according to five criteria: residual/market value, environmental burden, weight, quantity and ease of disassembly. Finally, Kazancoglu et al. (2018) proposed a criteria for Green Supply Chain Management (GSCM) performance assessment.

Table 4 highlights that MCDM and fuzzy methods have been rarely coupled with other approaches for measuring circular performances. They have been exploited mainly to assess materials and other resources (not neglecting energy and pollutions) from both an environmental and economic perspective. Moreover, their focus was on the BoL stage.

Table 4. MCDM: variables, lifecycle stages and TBL dimensions involved

Authors	**Method**								**Variables**				**Lifecycle Stage**				**TBL**		
													BoL		**MoL**	**EoL**			
	DEA /I-O	**DfX /GL**	**LCA/ LCI/ LCIA**	**MCDM/ fuzzy methods**	**Em, Ex**	**Simulation/ DES**	**MFA/ MCA/ MFCA**	**Other**	**E**	**M**	**Other Res**	**P**	**Product D&D and strategic evaluation**	**Manufacturing**			**Env**	**Econ**	**Soc**
(Petit et al., 2018)			x	x				CSR	x	x	x	x		x	x	x	x	x	x
(Ng and Martinez Hernandez, 2016)				x				PM	x	x	x	x	x	x	x		x	x	
(Shen et al., 2013)				x					x	x	x	x	x				x		
(Kazancoglu et al., 2018)				x					x	x	x	x	x				x	x	x
(Olugu and Wong, 2012)				x						x	x	x	x				x	x	
(Xu et al., 2018)				x						x			x				x	x	x
(Iakovou et al., 2009)				x					x	x						x	x	x	
(Wibowo and Grandhi, 2017)				x						x	x		x				x	x	
			1	**8**				**2**	**5**	**8**	**6**	**5**	**6**	**2**	**2**	**2**	**8**	**7**	**3**

CSR= Corporate Social Responsibility; PM=Process Modelling

3.1.3 DfX and guidelines

Others focused on the design phase for enabling circularity (Akinade et al., 2017; Favi et al., 2017; Grimaud et al., 2017; Issa et al., 2015; Lee et al., 2014; Oliveira et al., 2018; Santini et al., 2010), by adopting Design for X (DfX) approaches and guidelines. Oliveira et al. (2018) proposed strategic CE guidelines, guiding on the formulation of generic CE performance parameters. Akinade et al. (2017) proposed 43 Design for Disassembly (DfD) Critical Success Factors (CSF) for an effective material recovery in the construction industry. Santini et al. (2010) proposed a disassembly and composition analysis supported by Design for Recycling for End-of-Life Vehicles (ELVs). Lee et al. (2014) proposed an innovative approach – based on Design for End-of-Life (DfEoL) – supporting designers during the definition EoL performances related with each design alternative. Issa et al. (2015) selected and systematized a set of Environmental Performance Indicators (EPI), basing on selected lifecycle stage, environmental aspects and type of measure (absolute and relative). Finally, Favi et al. (2017) used DfX approaches (DfD, DfEoL) for providing new EoL indexes evaluating the feasibility of different EoL scenarios.

Table 5 presents how DfX approaches contribute to the CE performance assessment. In general, DfX has been coupled with LCA and MFA approaches – mostly contributing in the design and development of products – and providing guidelines for a strategic evaluation of BoL and EoL stages. Products' materials composition is the main object of these approaches, especially from an environmental view.

Table 5. DfX/GL: variables, lifecycle stages and TBL dimensions involved

Authors	**Method**								**Variables**				**Lifecycle Stage**				**TBL**		
													BoL		**MoL**	**EoL**			
	DEA /I-O	**DfX /GL**	**LCA/ LCI/ LCIA**	**MCDM/f uzzy methods**	**Em, Ex**	**Simul ation/ DES**	**MFA/ MCA/ MFCA**	**Oth er**	**E**	**M**	**OtherRe s**	**P**	**Product D&D and strategic evaluation**	**Manufac turing**			**Env**	**Econ**	**Soc**
(Oliveira et al., 2018)		x								x			x				x	x	
(Grimaud et al., 2017)		x	x				x			x			x				x	x	x
(Akinade et al., 2017)		x								x			x			x	x		
(Santini et al., 2010)		x								x						x	x	x	
(Lee et al., 2014)		x							x	x	x	x	x			x			
(Issa et al., 2015)		x							x	x	x	x	x	x	x	x	x		
(Favi et al., 2017b)		x							x	x	x	x	x			x	x	x	
		7	**1**				**1**		**3**	**7**	**3**	**3**	**6**	**1**	**1**	**5**	**6**	**3**	**1**

3.1.4 DEA and Input-Output models

Some more experts decided to measure variables involved in a system. Some authors (Expósito and Velasco, 2018; Mardani et al., 2017; Motevali Haghighi et al., 2016; Pagotto and Halog, 2015; Park et al., 2016) exploited Input-Output (I-O)-related models (Leontief, 1986), as Data Envelopment Analysis (DEA). Others (Franklin-Johnson et al., 2016; Grimaud et al., 2017; Pauliuk, 2018; Voskamp et al., 2016) recurred to MFA and MFCA approaches. Mardani et al. (2017) proposed DEA as a tool for analysing energy efficiency issues related with different Decision-Making Units (DMU). Expósito and Velasco (2018) proposed a radial DEA model, by applying it to municipal solid waste recycling processes. Pagotto and Halog (2015) combined DEA, I-O approaches and MFA for proposing a new approach evaluating eco-efficiency performances. Finally, Motevali Haghighi et al. (2016) built a hybrid Balanced Score Card (BSC) - DEA framework for evaluating performances in sustainable supply chains.

Table 6 shows that this kind of approaches were exploited for measuring all the variables involved in a system, from production up to disposal. Again, the perspective is mostly focused on the environment.

Table 6. DEA/I-O: variables, lifecycle stages and TBL dimensions involved

Authors	**Method**								**Variables**				**Lifecycle Stage**				**TBL**		
													BoL		**MoL**	**EoL**			
	DEA /I-O	**DfX / GL**	**LCA/ LCI/ LCIA**	**MCDM/ fuzzy methods**	**Em, Ex**	**Simulation/ DES**	**MFA/ MCA/ MFCA**	**Other**	**E**	**M**	**Other Res**	**P**	**Product D&D and strategic evaluation**	**Manufacturing**			**Env**	**Econ**	**Soc**
(Mardani et al., 2017)	x								x					x	x		x		
(Expósito and Velasco, 2018)	x									x						x	x		
(Pagotto and Halog, 2015)	x						x		x	x	x	x		x			x	x	
(Motevali Haghighi et al., 2016)	x							BSC	x	x		x		x	x		x	x	x
(Park et al., 2016)	x		x		x				x	x	x	x		x			x	x	x
	5		**1**		**1**		**1**	**1**	**4**	**4**	**2**	**3**		**4**	**2**	**1**	**5**	**3**	**2**
BSC= Balanced Score Card																			

3.1.5 MFA

Considering the gathered papers, MFA is not so commonly adopted by the experts to assess CE performances. However, some interesting examples exist. (Franklin-Johnson et al., 2016) proposed a new index for environmental performance assessment linked to CE, by combining a non-monetary (a longevity based method) and MFA approaches. Voskamp et al. (2016) applied some modification to the classic MFA method for conducting a comprehensive assessment of urban metabolism, based on the concepts of Direct Material Input (DMI) and Domestic Material Consumption (DMC).

Table 7 shows that, similarly to DEA/I-O methods, also MFA considers all the variables involved in a system along the entire lifecycle (almost neglecting product D&D), from an environmental and economic view.

Table 7. MFA/MCA/MFCA: variables, lifecycle stages and TBL dimensions involved

Authors	**Method**								**Variables**				**Lifecycle Stage**				**TBL**		
													BoL		**MoL**	**EoL**			
	DEA /I-O	**DfX /GL**	**LCA/ LCI/ LCIA**	**MCDM/ fuzzy methods**	**Em, Ex**	**Simulation/ DES**	**MFA/ MCA/ MFCA**	**Other**	**E**	**M**	**OtherRes**	**P**	**Product D&D and strategic evaluation**	**Manufacturing**			**Env**	**Econ**	**Soc**
(Pauliuk, 2018)			x				x		x	x	x	x		x	x	x	x	x	
(Grimaud et al., 2017)		x	x				x			x			x				x	x	x
(Franklin-Johnson et al., 2016)							x	LBM		x					x	x	x		
(Pagotto and Halog, 2015)	x						x		x	x	x	x		x			x	x	
(Voskamp et al., 2016)							x		x	x	x	x			x	x	x	x	
	1	**1**	**2**				**5**	**1**	**3**	**5**	**3**	**3**	**1**	**2**	**3**	**3**	**5**	**4**	**1**
LBM= Longevity Based Method																			

3.1.6 Emergy- and exergy-based approaches

Some experts focused on measuring just one of the variables involved in a system (e.g. energy), by exploiting concepts as emergy and exergy (Huysman et al., 2017; Jamali-Zghal et al., 2015; Pan et al., 2016). In the first case, (Pan et al., 2016) exploited emergy for evaluating recycling and reuse benefits in industrial parks through several indexes. In the second case, (Huysman et al., 2017) introduced the Circular economy Performance Indicator (CPI), a CE-related index able to measure the minimum energy required for making a product. CPI considers exergy of natural resources as the ratio of actual environmental benefits related with current waste treatment processes and ideal environmental benefits. An intermediate method is the one proposed by (Jamali-Zghal et al., 2015) combining an emergy evaluation with Exergetic Life Cycle Assessment (ELCA)).

Table 8 shows that these energy-based approaches have been often paired with LCA for measuring energy-related variables (but without neglecting materials and pollution). Moreover, they are not focused on product D&D, but on the entire lifecycle. Mainly, the perspective has a strong focus on the environmental view.

Table 8. Em, Ex: variables, lifecycle stages and TBL dimensions involved

Authors	Method								Variables				Lifecycle Stage				TBL		
													BoL		MoL	EoL			
	DEA /I-O	DfX / GL	LCA/ LCI/ LCIA	MCDM/ fuzzy methods	Em, Ex	Simulatio n/DES	MFA/ MCA/ MFCA	Oth er	E	M	Other Res	P	Product D&D and strategic evaluation	Manu factur ing			Env	Econ	Soc
(Pan et al., 2016)					x				x			x			x	x	x	x	
(Huysman et al., 2017)			x		x				x	x						x	x		
(Park et al., 2016)	x		x		x				x	x	x	x		x			x	x	x
(Jamali-Zghal et al., 2015)			x		x				x	x				x		x	x		
	1		**3**		**4**				**4**	**3**	**1**	**2**		**2**	**1**	**3**	**4**	**2**	**1**

3.1.7 DES/Simulation

Few works adopted simulation approaches (e.g. Discrete Event Simulation (DES) and process simulation), by combining them with LCA (Gbededo et al., 2018; Sénéchal, 2017). More in detail, (Gbededo et al., 2018) applied DES and holistic Life Cycle Sustainability Assessment (LCSA) for measuring Sustainable Product Development (SPD) and Sustainable Performance Assessment (SPA) contexts. Sénéchal (2017) used an eco-value analysis matrix for building a framework for measuring performances in Sustainable Condition-Based Maintenance (SCBM).

Table 9 shows a quite distributed focus on DES/simulation methods along all the variables and lifecycle stages. Basing on these few data, it is not possible to say anything about these approaches.

Table 9. DES/Simulation: variables, lifecycle stages and TBL dimensions involved

Authors	**Method**								**Variables**				**Lifecycle Stage**				**TBL**		
													BoL		**MoL**	**EoL**			
	DEA /I-O	**DfX / GL**	**LCA/ LCI/ LCIA**	**MCDM/ fuzzy methods**	**Em, Ex**	**Simulation/ DES**	**MFA/ MCA/ MFCA**	**Other**	**E**	**M**	**Other Res**	**P**	**Product D&D and strategic evaluation**	**Manufacturing**			**Env**	**Econ**	**Soc**
(Sénéchal, 2017)						x			x	x	x	x			x		x	x	x
(Gbededo et al., 2018)			x			x		SPD, SPA	x	x	x	x	x			x	x	x	x
			1			**2**		**1**	**2**	**2**	**2**	**2**	**1**		**1**	**1**	**2**	**2**	**2**
SPD= Sustainable Product Development; SPA= Sustainable Performance Assessment																			

3.1.8 Other approaches

Some assessments done in the construction industry adopted industry-specific methods for measuring performances of building materials (Akanbi et al., 2018), by combining either a real estate appraisal with LCA (Fregonara et al., 2017). Alternatively, AHP was adopted as a basis for implementing a sustainability assessment framework for modular buildings (Kamali et al., 2018). In particular, (Fregonara et al., 2017) developed a set of economic and environmental indexes supporting designers during decision-making processes. Following a similar logic, Kamali et al. (2018) evaluated the sustainability of buildings, by calculating several Sustainability Performance Criteria (SPC). Li (2011) used AHP for conducting a comprehensive evaluation on CE performances of eco-industrial parks. Yang et al. (2011a, 2011b) used factor analysis for developing a CE evaluation index based on information about energy consumption, resources recycling and reuse, environmental protection, costs and social aspects. (Delogu et al., 2017) performed a sensitivity analysis on different dismantling scenarios about recyclability and recoverability of ELVs. Berzi et al. (2016) used ISO 22628 and UNIFE guidelines, adapted from railway sector, for proposing an EoL performance evaluation method. (Han et al., 2017) adopted SNA for studying how CE measures can support innovation in the aluminium industry. Awasthi et al. (2018) used regression models for modelling the relation between e-waste quantities and economic development.

Table 10 shows a heterogeneous set of approaches. They attempt to measure all the variables of a system within the whole lifecycle. In general, the focus is on products' materials composition, with a prevalent perspective on environmental issues.

Table 10. Other approaches: variables, lifecycle stages and TBL dimensions involved

Authors	**Method**								**Variables**				**Lifecycle Stage**				**TBL**		
													BoL		**MoL**	**EoL**			
	DEA/ I-O	**DfX / GL**	**LCA/ LCI/ LCIA**	**MCDM/ fuzzy methods**	**Em, Ex**	**Simulation/ DES**	**MFA/ MCA/ MFCA**	**Other**	**E**	**M**	**Other Res**	**P**	**Product D&D and strategic evaluation**	**Manufacturing**			**Env**	**Econ**	**Soc**
(Han et al., 2017)								SNA	x	x	x	x			x	x	x	x	
(Petit et al., 2018)			x	x				CSR	x	x	x	x		x	x	x	x	x	x
(Awasthi et al., 2018)								RM		x						x	x	x	x
(Akanbi et al., 2018)								BWPE		x			x			x	x		
(Gbededo et al., 2018)			x			x		SPD, SPA	x	x	x	x	x			x	x	x	x
(Yang et al., 2011b)								FA		x					x	x	x	x	x
(Yang et al., 2011a)								FA		x					x	x	x	x	x
(Li, 2011)								ANP		x			x				x	x	x
(Ng and Martinez Hernandez, 2016)				x				PM	x	x	x	x	x	x	x		x	x	
(Fregonara et al., 2017)			x					REA	x	x	x	x	x				x	x	
(Franklin-Johnson et al., 2016)							x	LBM		x					x	x	x		
(Motevali Haghighi et al., 2016)	x							BSC	x	x		x		x	x		x	x	x
(Kamali et al., 2018)								AHP	x	x	x	x	x	x	x	x	x	x	x
(Berzi et al., 2016)								SA		x	x					x	x		
(Delogu et al., 2017)								SA	x	x	x	x				x	x		
	1	**3**	**2**	**2**		**1**	**1**	**15**	**8**	**15**	**8**	**8**	**6**	**4**	**8**	**11**	**15**	**11**	**8**

SNA= Social Network Analysis; CSR= Corporate Social Responsibility; 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

The following Table 11 summarizes all the methodologies described in literature adopted for conducting CE performance assessments. Numbers demonstrate as LCA-based approaches, together with MCDM and DfX, are the most common methods.

Table 11. Most used methodologies to assess circular economy in the extant literature

Methodology	Occurrences
Life Cycle Assessment (LCA), Life Cycle Inventory (LCI), Life Cycle Impact Assessment (LCIA)	15
Multi-Criteria Decision Making (MCDM) approach/ fuzzy methods	9
Design for X (DfX) and Guidelines	7
Data Envelopment Analysis (DEA)/ input-output	5
Material Flow Analysis (MFA)/ Material Cost Analysis (MCA)/ Material Flow Cost Accounting (MFCA)	5
Energy (emergy, exergy) approach	4
Simulation/ Discrete Event Simulation (DES)	2
Factor analysis (FA)	2
BIM-based approach (BWPE) and real estate	2
Analytic Hierarchic Process (AHP)/Analytic Network Process (ANP)	2
Social Network Analysis (SNA)	1
Corporate Social Responsibility (CSR)	1
Regression model (RM)	1
Sustainable Product Development (SPD) and Sustainable Performance Assessment (SPA)	1
Process modelling (PM)	1
Longevity based method (LBM)	1
Balanced Score Card (BSC)	1

4. Discussion

Starting from the results of the literature review, the authors built a framework to position the existing methodologies and be able to understand which areas are covered and which ones present shortage of contributions. This positioning framework is composed by three dimensions related with the most important criteria analysed:

- Product Lifecycle Stages: which lifecycle phases (i.e. beginning, middle or end of life) are considered for CE evaluation;
- Variables: which types of variables (declined in energy, material and other resources) are considered and measured;
- Circularity Degree: the perspective (economic, environmental or social) used to analyse variables in the methodologies.

Trying to summarize the findings coming from this extensive literature review, the papers analysed reveal a strong orientation of the used methodologies on the environmental aspect of the TBL of Sustainability (WCED, 1987) (Table 12). Indeed, all the contributions involve the environmental perspective, either alone (31,1%) or combined with the economic one (35,5%) or embedded in the entire triple perspective (33,3%).

Table 12 Circular Economy performance assessment: categorization based on the Sustainability Triple Bottom Line (TBL)

Environmental	**Economic**	**Social**	**Environmental, Economic**	**Environmental, Social**	**Economic, Social**	**All**
14	-	-	16	-	-	15

The strong tendency of these methodologies to focus on the environmental level led the authors to shift their attention on the variables involved in the circular systems considered, by either differentiating among materials (constituting the system to be delivered), energy and other resources (used to produce the product or system) - not neglecting in the analysis the final output pollution - or considering a combination of them. Again, there is a strong focus on only one element, i.e. material (both those constituting the product and the other resources used during their production and operation). This confirms the importance of such type of variables in the circularity performance context, since a continuous flow of technical and biological materials through the 'value circle' is considered in CE (The Ellen MacArthur Foundation, 2015). As shown in Table 13, only 2 out of 45 papers divert the focus on the energy variable alone (4,44%). All the other articles involve material in their evaluation, either alone (26,6%) or combined to energy (8,88%), to other resources (15,5%) or to both (44,4%).

Table 13 Circular Economy performance assessment: categorization based on variables (Material, Energy, Other resources)

Energy	**Material**	**Other Resources**	**Energy, Material**	**Energy, Other Resources**	**Material, Other Resources**	**All**
2	12	-	4	-	7	20

Finally, the papers selected have been analysed in terms of lifecycle stage considered for conducting the circular performance assessment, differentiating among BoI, MoL and EoL. From Table 14 it is noticeable a slender propensity to measure the circular performance either during the BoL (28,8%) or EoL (17,7%): indeed, only one time (2,2%) systems have been analysed during the single MoL stage. Most of the cases analysed (51%) represent instead attempts to evaluate the circular performance in a combination of more lifecycle stages together, either in couples or all together.

Table 14 Circular Economy performance assessment: categorization based on lifecycle stages (BoL, MoL, EoL)

BoL	MoL	EoL	Bol, MoL	BoL, EoL	MoL, EoL	All
13	1	8	6	5	6	6

Wrapping up, nowadays, still too few industries consider that their manufacturing systems are inspired by biological models where materials and energies are used not only efficiently but also effectively (Despeisse et al., 2012). By analysing resource flows, it is possible to identify solutions to reduce environmental impact and, at the same time, generate economic savings. However, CE does not mean only Industrial Symbiosis and systemic optimization. It also means life cycle optimization. Speaking about "self-regenerating economy" it is necessary to work at system level and at single product level at the same time, with the possibility to go into detail and analyse the single production phase and the single resource flow. This way, it is possible to understand where the improvements are. For this reason, a quantitative analysis model must be proposed with the aim to keep the product as the protagonist of the analysis in terms of CE and to calculate the circularity degrees. The literature analysis carried out shows the lack of methodologies regarding the overall evaluation of CE benefit, unveiling the difficulty of researchers to consider the large number of different variables composing and called along the entire lifecycle of a system, affecting different levels of analysis (environmental, economic and social).

5. Conclusions

This research operated a systematic review of the extant literature with the aim to understand which the methods are used so far to measure and assess the circular performance of a system and how they have been used in practice by researchers.

The analysis of the literature confirms that circular models can be measured taking care of different aspects. For example, DfX and Guidelines are used to empower specifically the product design and development and to give strategic directions to shift the linear lifecycle into a circular one. Other kind of approaches, like LCA, MFA, DEA/I-O, MCDM and DES are aimed at considering and evaluating all the possible variables involved in the system, along almost the entire lifecycle: indeed, in this case the development phase leaves the floor to the following stages composing the lifecycle, starting from production, through use, system operation and service delivery up to disposal.

It has also to be highlighted that several types of industries have been considered by researchers to apply and test in practice their researches, affecting in their analysis not only the choice of different methods (CSR, RM, CSR, FA, AHP, SNA, BWPE, BSC, etc) and their combination with those used more commonly in the circular context but also the industrial symbiosis level considered. Not only single companies but also industrial parks, global supply chains, urban territory and municipal solid wastes were taken in account, giving the chance to approach very different contexts in which circular business models have been adopted, considering in the measurement of the performance also specific building blocks as reverse logistics and particular systems conditions.

The final main result, a positioning framework built on the base of the dimensions detected in the literature review, has been proposed to map the CE performance assessment methods according to the TBL perspective, variables involved and lifecycle stage. This will enable to identify the gaps to be covered and filled through a new circular performance assessment method.

Indeed, both the analysis and the resulting positioning framework contribute to the research domain providing theoretical directions about the dimensions to be considered in the development of a holistic methodology able to systematically and practically measure and assess the circularity degree of a given system and to take in account all the heterogeneous resources involved in its lifecycle. Further researches are hence needed to develop this kind of methodology, paved on the framework conceived and proposed in this research, also providing a set of Key Performance Indicators (KPI) suitable to the assessment of the circularity performance. These KPIs can deal with the circularity degree of the resources presents within the product life cycle and can also support the quantification of those that are the economic and environmental benefits of the CE. Indeed, they can be used in different application fields. From a regulations and reporting perspective, some examples can be the creation of a product certification system related to the circularity of resource flows, the internal reporting and benchmarking in companies or the support in the creation/enrichment of databases useful for LCA or similar analysis conduction. From a companies' portfolio circular innovation perspective (both for completely new products and incremental improvements of existing products), these circular KPIs can support not only the decision making process along the design of new products but also the comparison of different versions of the same product based on their degree of circularity and the benefits they can bring. Companies would be able to compare different products based on their circularity and on benefits they can achieve.

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as an official position of the supporting organization, but it reports just the point of view of the authors.

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