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USE OF LIFE CYCLE ASSESSMENT IN THE CONTEXT OF CIRCULAR ECONOMY: A LITERATURE REVIEW

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ABSTRACT

Circular Economy (CE) is currently a popular concept promoted by companies, countries and the European Union, and represents a rationality of greater resource efficiency, as opposed to the linear rationality of extract-produce-consume-discard. The literature reports several initiatives related to CE and the need to quantify the real benefit of these initiatives. Life Cycle Assessment (LCA) is a tool that allows quantifying the environmental impact of products and services and can contribute to proving the benefits of CE. The purpose of this paper is to analyze the use of LCA in the context of CE. For this, a literature review was performed in the SCOPUS and Web of Science databases, using the terms “life cycle” AND “circular economy”. All articles published up to 2017 were considered. There was a prevalence of studies carried out on the European continent, especially in Spain, and studies related to waste management. The exploratory research highlighted the importance of LCA for the promotion of CE, since it allows quantifying the environmental benefits of its strategies – in the scope of supply and production, sustainable consumption and waste management –, strengthening the propositions of CE. In addition, the CE used was observed as a basis for the definition of alternative scenarios that were analyzed with the LCA.

Keywords: Circular economy, life cycle assessment, literature review.

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INTRODUCTION

Circular Economy (CE) is an alternative to the current economic model, which is based on a linear system of production-consumption-disposal of goods and services, where more and more natural resources are extracted to produce new raw materials used in the production of new products that are discarded at the end of their useful life. Although there are studies dedicated to understanding this model (Geissdoerfer et al., 2017; Kirchherr et al., 2017; Prieto-Sandoval et al., 2018), The consensus exists when it comes to the paradigm shift that is linked to CE, as it requires new ways to produce and consume products. This implies a change in rationality that permeates all stages of the life cycle, from product design and sourcing to final waste treatment and disposal. In addition, there is a need for a multi-targeted approach to sustainable development, resource and energy recirculation, resource demand minimization and waste recovery (Prieto-Sandoval et al., 2018). The circular economy limits the flow of production to a level that nature tolerates and utilizes ecosystem cycles in economic cycles, while respecting their natural reproduction rates (Korhonen et al.,2018).

The concept of CE originates from several schools and lines of thought considered the basis of the discussion of Sustainable Development, such as Industrial Ecology, Life Cycle Management, among others. For this reason, numerous CE concepts are found in recent literature. Kirchherr *et al.* (2017), for example, conceptualize CE as an economic system based on business models that replace the concept of "end of life" with reducing, reusing, recycling and recovering materials in the production, distribution and consumption processes operating at the micro level (products, companies and consumers), meso level (eco-industrial parks) and macro level (cities, regions and countries), in order to achieve Sustainable Development. Geissdoerfer *et al.* (2017) consider CE as a regenerative system in which the input and output of waste, emissions and energy are minimized by narrowing material and energy flows through durable product design, maintenance, repair, reuse, remanufacturing and recycling. Stahel (2016) says CE transforms end-of-life goods into resources for others, closing loops and minimizing waste. This means a shift in economic logic because it replaces production with sufficiency: "Reuse what you can, recycle what can't be reused, repair what's broken, and rebuild what can't be fixed." Such diversity of concepts, however, does not undermine the understanding that CE is directly associated with the balanced integration between economic performance, social inclusion and environmental resilience, that is, sustainability.

According to Ellen Macarthur Foundation (2015), the CE is based on three principles: (i) preserving and enhancing natural capital by controlling the stock of finite natural resources and balancing the flow of renewable resource use; (ii) optimizing resource performance to maximize the value and usefulness of products, components and materials; and (iii) stimulating the effectiveness of the system by identifying and removing negative externalities of the economy.

In the absence of a single indicator for measuring the circularity of the economy, the French Agency for Energy and Environment (ADEME) has set ten key indicators to measure progress towards a circular economy. It sought to encompass the multiple dimensions at all stages of the life cycle of resources, products and services. The defined indicators were: (i) material consumption per capita, (ii) resource productivity, (iii) environmental seals, (iv) number of industrial and territorial ecological projects, (v) vehicle sharing rate, (vi) waste generation, (vii) household expenditures on product maintenance and repair, (viii) amount of waste sent to landfill, (ix) use of secondary materials and (x) CE jobs (repair, reuse, waste recycling, rental services, etc.). These indicators are grouped into three action areas and seven pillars established by ADEME (SOeS, 2017) (Figure 1).

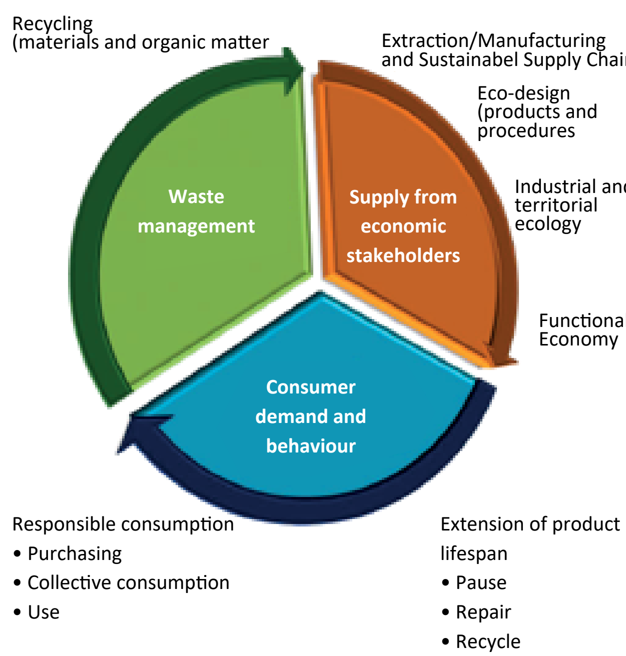

Figure 1. Circular Economy Areas and Pillars
Source: SOeS (2017).

Instructions that assist in more detailed CE monitoring can be found in the requirements of British Standard BS 8001: 2017. This standard is the world's first standardized guide for implementing circular economy principles in organizations based on systemic thinking, innovation, management, collaboration, value optimization and transparency (BSI Group, 2017).

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The importance of CE has increased substantially in recent years, both by the recognition of countries and its relevance (Korhonen, Honkasalo e Seppälä, 2018), and the increased use of this term in academic work (Homrich *et al.*, 2018). Despite these initiatives, recent reviews of CE show that, despite the growing interest of researchers and practitioners on this topic, research on indicators and methodologies for measuring the implementation of CE strategies is still in its early stages (Elia *et al.*, 2017)the circular economy (CE.

Life Cycle Assessment (LCA) is a valuable tool for quantifying and reporting the benefits of CE (Strothman; Sonnemann, 2017). In this context, this paper analyzed articles published until 2017 that addressed Circular Economy and used LCA to present a profile of these publications and to analyze how LCA is being used in CE studies, having as reference the CE pillars defined by the French Energy and Environment Agency (ADEME) (SOeS, 2017).

1. METHODOLOGY

The research question of this paper is: How has Life Cycle Assessment been used in articles related to Circular Economy? To answer this question, a bibliographic search was performed in the SCOPUS and Web of Science databases, using the terms "Life Cycle" AND "Circular Economy". The search identified articles containing these terms in the title, abstract, or keyword fields.

The following inclusion criteria were used: (i) articles published by the end of 2017; (ii) articles that present an application of Life Cycle Assessment and highlight the term Circular Economy. The prominence of the term "Circular Economy" was observed initially by the presence of the term in the title, abstract or keyword and, later, during the full reading of the articles, by the use of the term in the text, especially in the discussion and conclusion. Review articles, non-indexed studies, conference papers, book chapters, reports, etc. were excluded. In addition, there are studies with incomplete text available and duplicate articles.

The selected studies were analyzed and classified according to the areas of action and the CE pillars defined by the French Agency for Energy and Environment (ADEME), which considers the CE as an economic system of exchange and production in all phases of the life cycle (SOeS 2017). ADEME has defined seven pillars, grouped into three action areas (SOeS 2017), which assist in monitoring the circularity of the economy (LCiP 2016): (i) sustainable supply, (ii) ecodesign, (iii) promotion of energy and resource efficiency and (iv) industrial symbiosis in the area of "supply and production"; (v) consumption and sustainable use of products; (vi) increased durability (considering product reuse, recovery or repair) in the "consumer demand and behavior" area; and (vii) recycling, organic recovery or energy recovery in the "waste management" axis area. Thus, the review of the studies was based on the identification of the CE strategy approached, based on the ADEME classification, and on the analysis of the contribution of LCA to the promotion of CE.

The selected articles were compiled in a spreadsheet and the following information was extracted: the application sector; the areas of activity and pillars defined by ADEME; country where the study was conducted; journal that published the study; software used and the boundaries defined in the studies.

2. RESEARCH RESULTS

Selection of articles

The execution of the bibliographic search allowed identifying 437 articles in the two searched bases, of which 124 were present in both bases (Figure 2). The total of 31 articles was selected after applying the inclusion and exclusion criteria. Some excluded articles applied other tools, such as Material Flow Analysis (Diener; Tillman, 2016; Sadhukhan; Martinez-Hernandez 2017; Sun et al. 2017), Global Resource Indicator (Adibi et al. 2017) and the Gaia Refiner Indicator Framework (Rönnlund et al. 2016).

Chart 1 gives a brief description of the articles analyzed and their classification according to the sector of application.

Regarding the place where the studies published in the selected articles were performed, there was a considerable prevalence of European countries, especially Spain, with seven articles. Figure 3 also shows the presence of four articles in the "Europe" class, which refers to studies carried out in more than one country on the European continent. Also noteworthy are Italy and China with three articles each.

The selected studies came from 19 different journals, most notably the Journal of Cleaner Production, with approximately 23% of articles, followed by Resources, Conservation and Recycling with 12.9%. The journals Waste Management and Research, Science of the Total Environment, and The International Journal of Life Cycle Assessment published two articles each out of the 31 selected. The other journals published only 1 article (Figure 4).

Normally Life Cycle Assessment studies are developed with the help of some software, although 11 articles did not explain the software used. Figure 5 presents the software identified in 20 articles of the selected studies. SimaPro (50%) and GaBi (40%) software stand out.

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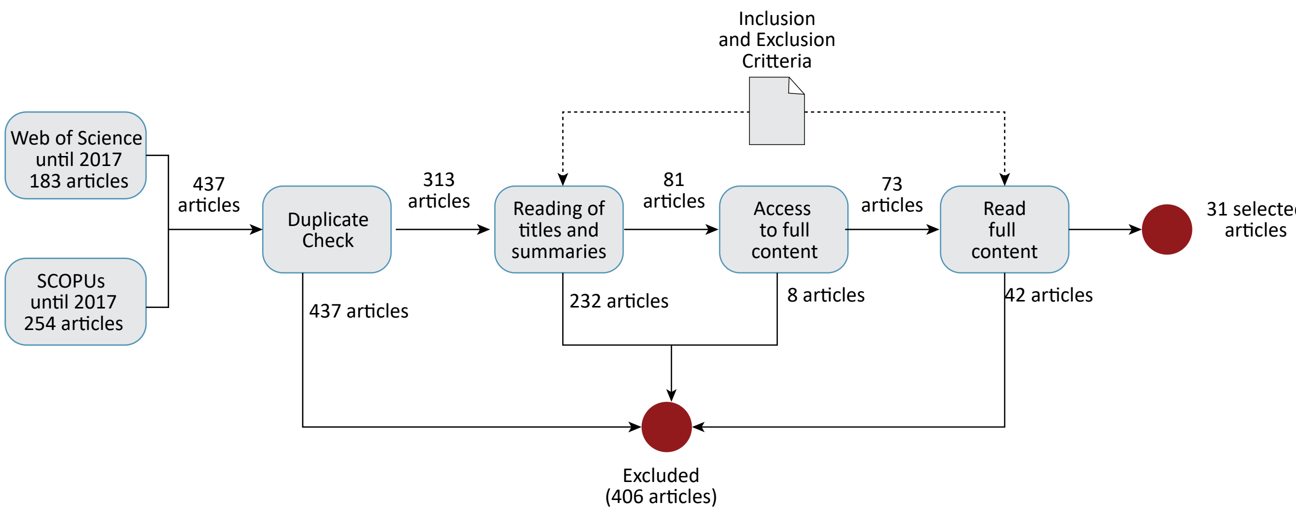

Figure 2. Selection of articles

Source: the authors.

Chart 1. List of selected articles with their application sectors

x	Reference	Application sector	No	Reference	Application sector
1	Angelis-Dimakis et al., 2016	Water use system	17	Lausselet et al., 2017	Urban solid waste
2	Broadbent, 2016	Steel recycling	18	Niero et al., 2017	Manufacturing industry (packaging)
3	Castellani et al., 2015	Reuse of consumer goods	19	Niero; Olsen, 2016	Manufacturing industry (packaging)
4	Catalán et al., 2017	Leather industry	20	Noya et al., 2017	Farming
5	Daddi et al., 2017	Tannery Cluster	21	Oldfield et al., 2016	Food Waste Management
6	Delgado-Aguilar et al., 2015	Pulp and Paper Industry	22	Pan et al., 2017	Alkaline Solid Waste
7	Dominguez et al., 2017	Gray water reuse	23	Ren, et al., 2017	Manufacturing industry (cement)
8	Edwards et al., 2017	Urban solid waste	24	Rigamonti et al., 2017	Electrical and Electronic Waste
9	Garcia-Herrero et al., 2017	Manufacturing Industry (Chlor--Alkali)	25	Roest et al., 2016	Water use system
10	Ghisellini et al., 2014	Farming	26	Seghetta, et al., 2016	Macroalgae biorefinery
11	Hadzic et al., 2017	Urban solid waste	27	Strazza et al., 2015	Food waste
12	Husgafvel, et al., 2016	Forest Waste	28	Tran et al., 2017	Battery Recycling
13	Iraldo et al., 2017	Home Appliances	29	Unger et al., 2017	Electro Electronic Waste
14	Krystofik et al., 2017	Manufacturing industry (office furniture)	30	Yu et al., 2015	Aluminum production
15	Laso et al., 2016a	Fish Industry	31	Zhang et al., 2017	Biofuel
16	Laso et al., 2016b	Fish Industry	-	-	-

Fonte: os autores.

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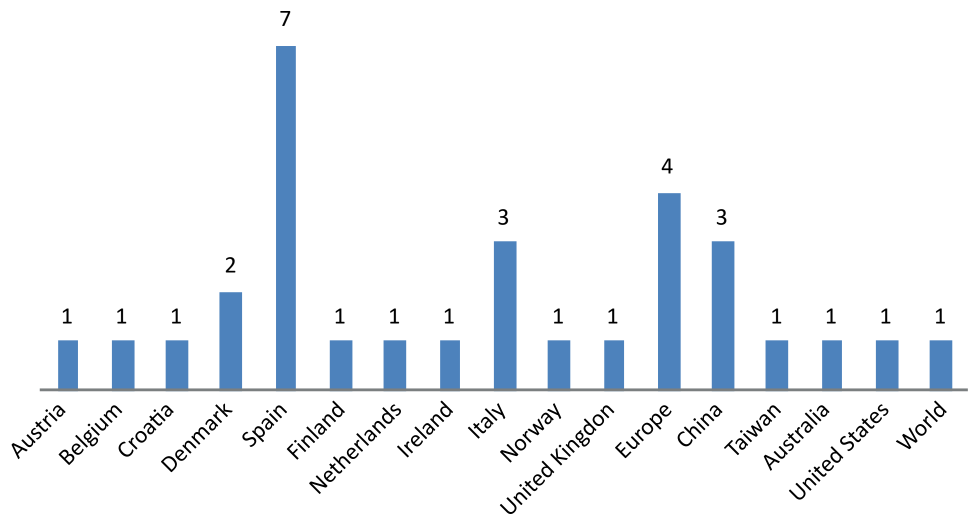

Figure 3. Countries where studies of selected articles were performed

Source: the authors.

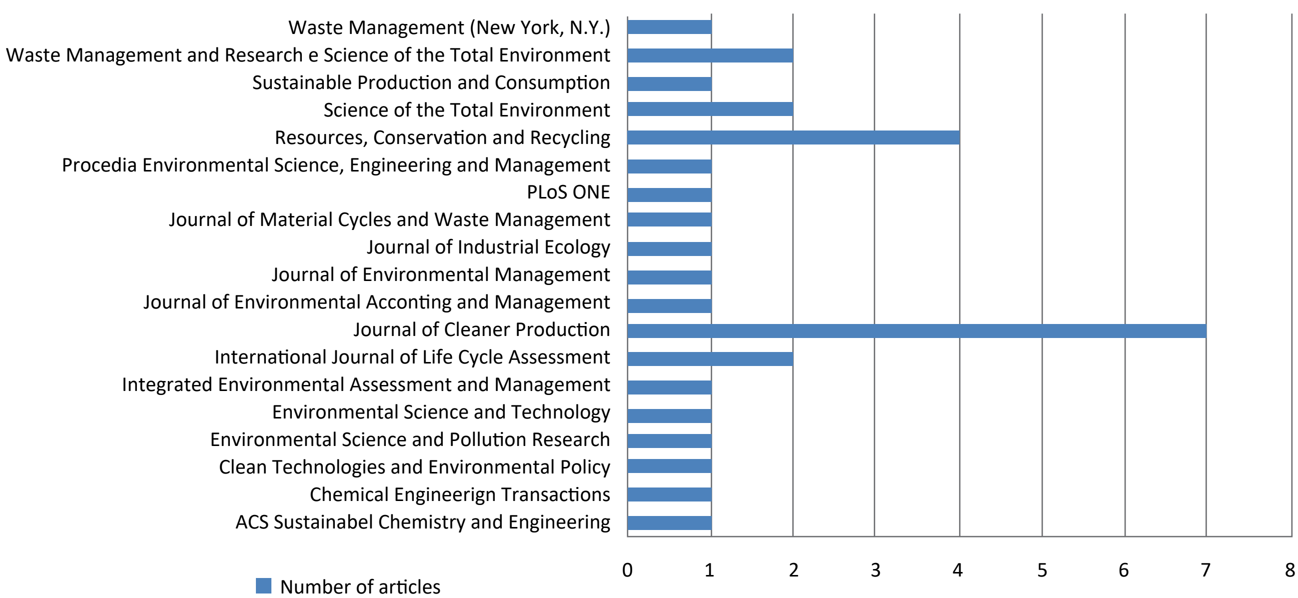

Figure 4. Scientific journals in which the selected articles were published

Source: the authors.

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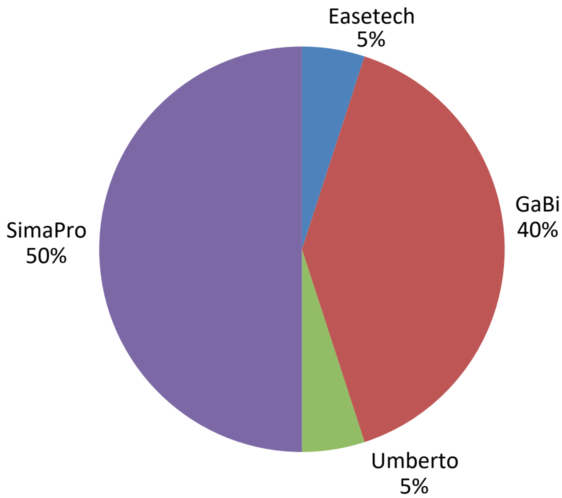

Figure 5. Software used in LCA application in selected articles
Source: the authors.

The studies were classified according to the scope adopted, as shown in Figure 6.

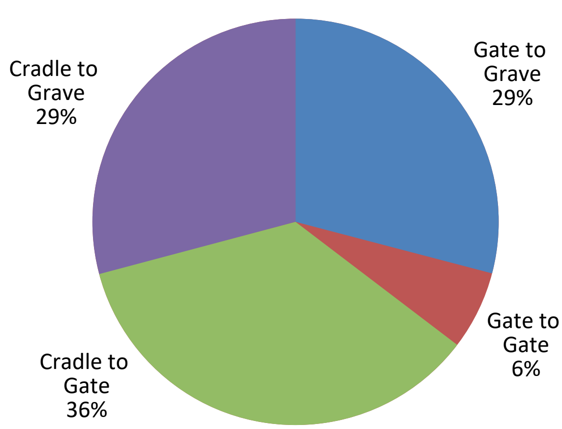

Figure 6. System boundaries used in LCA application in selected articles
Source: the authors.

The classification of studies according to the areas of action and the CE pillars defined by ADEME are presented in Chart 2.

3. RESULTS ANALYSIS AND DISCUSSION

Regarding the profile of the selected articles, there was a prevalence of studies focusing on waste management. These studies covered different wastes as municipal solid waste collected by a municipal management system (Hadzic *et al.*, 2017; Lausselet *et al.*, 2017), electronic waste (Rigamonti *et al.*, 2017; Unger *et al.*, 2017)recovery of secondary resources (materials and energy, organic waste (Edwards *et al.* 2017; Oldfield *et al.*, 2016; Strazza *et al.*, 2015)(a, leather production waste (Catalán *et al.*, 2017) and also a study dealing with resale of used products (Castellani et al, 2015). Studies on this theme stand out for their relevance in the context of the CE that seeks to “close cycles” (SOeS 2017) and the associated risks. (Moura *et al.*, 2015).

The studies observed were those focusing on industrial aluminum production (Niero; Hauschild, 2017; Niero; Olsen, 2016)representing the second largest source of aluminium scrap at global level, deserves a key role in the transition towards the circular economy. Life Cycle Assessment (LCA, on potassium chloride (Garcia-Herrero *et al.*, 2017)as valuable materials are lost as waste. Moving towards a circular economy and supporting efficient resource utilisation is essential for protecting the environment. The chlor-alkali industry is one of the largest consumers of salt, and efforts have been made to reduce its electricity use. Furthermore, KCl mining wastes have received increasing attention because they can be transformed into value-added resources. This work studies the influence of using different salt sources on the environmental sustainability of the chlor-alkali industry to identify further improvement opportunities. Rock salt, solar salt, KCl waste salt, vacuum salt and solution-mined salt were studied. Membrane cells in both bipolar and monopolar configurations were studied and compared to the emergent oxygen-depolarised cathode (ODC, on clinker production for the cement industry (Ren *et al.*, 2017) and on office furniture remanufacturing (Krystofik *et al.*, 2017). In addition to two articles that address industrial production in the context of a Local Productive Arrangement (LPA), also working the concept of industrial symbiosis (Daddi *et al.*, 2017; Yu *et al.*, 2015).

Studies related to water management were also present in three articles, two of which dealt with the analysis of different water supply systems (Angelis-Dimakis *et al.*, 2016; Roest *et al.*, 2016), and one addressed scenario analysis for gray water treatment and reuse (Dominguez *et al.*, 2017).

The studies carried out in South American countries were not present in the selection. There was a prevalence of studies conducted in Europe, especially Spain, with 7 articles, and studies conducted in more than one EU country, classified as “Europe”. Also noteworthy are Italy and China with 3 articles each. The presence of documents promoting the circular economy is believed to have contributed to this. The European Commission has recently finalized a comprehensive Action Plan for the transition to a Circular Economy in Europe, outlining a range of policy interventions needed throughout the product life cycle that should be considered in the short/medium term of policy development (Milios, 2017). China, for its part, was the first country to adopt circular economy legislation in 2008 (Korhonen *et al.*, 2018).

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Chart 2. Classification of studies by ADEME Action Areas and CE Pillars (SOeS 2017)

Action Areas	Pillars	References
Supply and production	Sustainable supply	Garcia-Herrero et al., 2017
		Ghisellini et al., 2014
		Seghetta et al., 2016
	Ecodesign	Delgado-Aguilar et al., 2015
		Niero et al., 2017
		Niero; Olsen, 2016
	Energy and resource efficiency	Angelis-Dimakis et al., 2016
		Pan et al., 2017
		Zhang et al., 2017
	Industrial symbiosis	Daddi et al., 2017
		Yu et al., 2015
Consumer demand and behavior	Sustainable consumption	Iraldo et al., 2017
	Increased durability (reuse, Recovery/repair)	Castellani et al., 2015
		Krystofik et al., 2017
Waste management	Recycling, Organic Recovery or Energy Recovery	Broa dbent, 2016;
		Catalán et al., 2017
		Dominguez et al., 2017
		Edwards et al., 2017
		Hadzic et al., 2017
		Husgafvel, et al., 2016
		Laso et al., 2016a
		Laso et al., 2016b
		Lausselet et al., 2017
		Noya et al., 2017
		Oldfield et al., 2016
		Ren, et al., 2017
		Rigamonti et al., 2017
		Roest et al., 2016
		Strazza et al., 2015
		Tran et al., 2017
		Unger et al., 2017

Source: The Authors.

Still in relation to the country of origin of the articles, the study of Broadbent (2016)carefully managing our finite natural resources is becoming critical. We must abandon the outdated \u2018take, make, consume and dispose\u2019 mentality and move toward a circular economy model for optimal resource efficiency. Products must be designed for reuse and remanufacturing, which would reduce significant costs in terms of energy and natural resources. Methods: To measure progress in achieving a circular economy, we need a life cycle approach that measures the social, economic and environmental impact of a product throughout its full life cycle\u2014from raw material extraction to end-of-life (EoL, which was classified in the "World" category because it is a study that analyzed the benefits of steel recycling in the context of a CE using global steel production data.

Regarding the journals that published the studies, it is interesting to note the performance of The International Journal of Life Cycle Assessment, a journal focused on LCA studies. It is possible that the specificity of the journal in the LCA tool contributed to the concept of Circular Economics, although the scientific community of LCA is increasingly interested in discussing the potential of using LCA in Circular Economy (Haupt; Zschokke, 2017).

It should be noted that the use of only two databases (Scopus and Web of Science), during the bibliographic research, directly influences this profile of the journals and articles found, as it is limited only to those indexed in these databases.

One of the steps in applying Life Cycle Assessment is defining the scope of the study. Among the scope specifications is the definition of system boundaries, which is to make clear which processes are part of the study. This definition of boundaries is classified considering the life cycle

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phases. A broader perspective considers all stages of the life cycle, from raw material (cradle) extraction to final disposal or (grave) waste recycling. A narrower boundary can be chosen that considers only part of the life cycle stages of the product or service studied, which can be: cradle to gate, considering the processes of extraction of raw materials up to a certain stage of the life cycle, such as the example of the completion of the product production process; gate to gate, covering only the processes of one or more intermediate phase of the life cycle, such as processes within the industry; or gate to grave, which in turn contains the processes from a given intermediate phase of the life cycle to final disposal.

The definition of the boundary depends on the objectives of the study. Studies involving waste management, for example, usually do not consider all stages of the life cycle (cradle to grave). On the other hand, studies with industrial focus that address the analysis of different processes or raw materials may, in this context, justify a smaller scope. Thus, this analysis did not seek to merit the definition of the scope defined in the analyzed studies, but only to present the profile as a way to guide future studies.

In general, LCA studies in the context of CE can be expected to have broader scopes, analyzing all the steps necessary to prove the benefits in a circular context. However, as reported, this definition depends on the purpose of the study, and a more restrictive scope is perfectly acceptable. Despite this, it draws attention to the fact that only 6% of the studies have the most limited scope (gate to gate) (Figure 6).

The classification of articles according to the CE pillars is presented in Table 2. It was observed that most articles (55%) present studies related to waste management. Overall, these articles use CE as a strategic framework in the waste management discussion, helping to define alternative treatment scenarios to bring the system closer to the cradle-to-cradle principle. Likewise, it was observed that LCA was used to quantify the environmental benefits of these scenarios and assist in choosing the best strategy, thus corroborating the observations of Contreras (2017), where LCA is considered a complementary tool to CE. Such studies covered different types of waste. Lausselet *et al.* (2017) and Hadzic *et al.* (2017) focused on USW. Hadzic and colleagues applied LCA to compare USW management scenarios to highlight environmental improvements resulting from the move from linear waste management system to CE. The LCA results confirmed the environmental benefits of anaerobic digestion of the organic fraction, material recycling and heat treatment of the residual fraction compared to landfill disposal. Unger *et al.* (2017) and Rigamonti *et al.* (2017) focused on the recovery of materials from Waste Electrical and Electronic Equipment (WEEE), which is considered an important contribution to CE, and the LCA allowed quantifying the environmental benefits associated with the recycling of these wastes, corroborating the need for increased recycling rate and reintroduction of secondary materials into the economy as a means of increasing the security of raw material supply, and may also assist in the definition of the European Union's CE policy. Organic waste was the most addressed in the studies (Edwards *et al.* 2017; Oldfield *et al.,* 2016; Strazza *et al.*, 2015). Strazza and colleagues evaluated the recycling of food waste for use in aquaculture and the LCA was applied to quantify the potential benefits of replacing traditional salmon feed inputs with cruise ship generated and processed food waste from a turbo-drying technology. Tran *et al.* (2017)which are an important waste stream, and aid the conservation of raw materials. Unlike existing studies on WPB management, which focus mainly on emissions, this case study uses a resource-oriented approach to thoroughly analyze the performance of a WPB collection and recycling scheme. This study focused on the WPB take-back and recycling system managed by Bebat in Belgium. Life cycle assessment was conducted using three different existing life cycle impact assessment (LCIA evaluated the potential environmental impacts of portable battery recycling, and the LCA allowed identifying that the battery collection and recycling system studied does not have benefits in terms of energy, but have considerable benefit in terms of recovery of metals and minerals, as well as identifying ways to further improve processes. In the context of industrial solid waste, Laso *et al.* (2016a; 2016b) applied LCAs to assess the environmental performance of two waste management alternatives: sardine meat valorization to produce pate and head and column valorization to produce fishmeal and fish oil. Catalán *et al.* (2017) focused on leather waste and LCA results indicated the most appropriate waste treatment scenario from the CE point of view.

Also, noteworthy, in the relationship between LCA and CE presented in the articles, the focus on research aligned with the "Supplies and Production" axis (11 articles, representing 35.5%). In the context of Sustainable Supply, for example, Garcia-Herrero et al. (2017) compared different sources for obtaining Potassium Chloride (KCl) for the Chlor-Alkali industry, demonstrating the importance of analyzing each stage of the chemical process life cycle. The LCA results have proven the benefits of CE with regard to waste utilization in this energy intensive industry. Although the focus was on paper recycling, the study of Delgado-Aguilar et al. (2015) can be classified into the ecodesign pillar as they have applied LCA to analyze the feasibility of incorporating lignocellulosic nanofibers in the paper in order to increase the number of cycles in which paper can be recycled while maintaining the relevant physical properties. In the area of energy and resource efficiency, Angelis-Dimakis et al. (2016) evaluated the eco-efficiency of eight water consumption systems and the LCA results allowed identifying the critical points of each system and, consequently, the opportunities for improvement for the most efficient use of the resource. Resource efficiency has been proven by Pan et al. (2017), which assessed the environmental and economic benefits through the application of LCA and LCC (Life Cycle Costing), the use of CO_2 emitted by the steel manufac-

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turing industry to treat alkaline waste from the steel industry for use in the cement production process. Daddi et al. (2017) evaluated the positive impact of industrial symbiosis actions on a tannery cluster in Italy, where the application of LCA quantified the environmental benefits of producing 1 m² of leather and reusing water from the clustered system, placing it as a fundamental decision support tool in initiatives related to Sustainable Development.

Perhaps due to the difficulty in setting sustainable consumption, only three articles are linked to the "consumer demand and behavior" axis. Iraldo *et al.* (2017) applied LCA and LCC to investigate whether and under what conditions the prolonged durability of energy intensive products is desirable from an environmental and economic perspective. To that end, they compared one durable option and one set as "standard" for two different products – refrigerator/freezer and household electric oven. According to the results of this study, if more durable products are almost always the economically preferred choice for the consumer, this is not always the case from an environmental point of view, for, only when the life-cycle production and end-of-life stages have very high impacts compared to the use phase, the most durable option is preferred, both economically and environmentally. Castellani *et al.* (2015) applied LCA to quantify avoided emissions from reusing products from a second hand store such as apparel and furniture. Krystofik *et al.* (2017), evaluated the environmental benefits of office furniture remanufacturing in order to maximize their value and usefulness. These LCA results indicated that remanufacturing is an environmentally preferable and economically viable business strategy. Specifically, the ability to upgrade, reconfigure, and customize previously obsolete products to meet current market demands enables life cycle extension beyond what is feasible with traditional manufacturing. In this sense, the study proved that such remanufacturing techniques not only expand potential environmental benefits, but also increase long-term economic viability in durable product markets.

4. FINAL CONSIDERATIONS

The review of the developed literature allowed identifying studies related to the application of LCA in the context of the CE that fit all the strategic pillars of the CE defined by ADEME, demonstrating the relevance of this joint use.

The analysis of the selected studies identified a predominance of studies carried out on the European continent, which demonstrates a greater maturity of European countries in the subject.

Several areas of application of the studies were identified, especially waste management. In addition, the publications came from 19 different journals. This demonstrates the diversity of joint applications between Life Cycle Assessment (LCA) and Circular Economy (CE).

Although CE is positioning itself as a vision capable of mobilizing business strategies and government plans, making it possible to highlight connections, flows and feedbacks between the systems, the challenge still remains to establish metrics capable of monitoring the circularity of the economy, that is, whether CE strategies are being achieved. In this sense, the review showed that LCA was used as a tool to quantify environmental impacts related to CE strategies. CE, in turn, appeared as a strategic guide for the definition of scenarios that were quantified with the aid of LCA. In this way, the tools are complementary and can, together, contribute to a continuous improvement towards greater circularity in the economy, with environmental benefits. Emphasis is given to the importance of LCA in the evaluation of waste treatment options, which, in the context of the circular economy, should be treated as resources for a restorative and regenerative economy.

LCA complementarity with CE is enhanced when the other methodologies are applied together. For this reason, it is recommended to extend the review to analyze the application of other methods in the context of the CE, not only in the environmental sphere but also in the other dimensions of sustainability.

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