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Review

Operational principles of circular economy for sustainable development: Linking theory and practice

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ABSTRACT

The scientific literature about circular economy (CE) is scarce yet, and both conceptual discussions and the development of practical strategies for its implementation are still emerging. Although CE systems are currently being implemented, CE goals and principles need to be better considered and translated into actions, and more coordinated actions among different levels of implementation are necessary. In this research we conduct a review of the scientific literature relative to CE and propose operational principles which join the theoretical goals of CE within the sustainable development framework to practical strategies of implementation. This research resulted in seven operational principles: i) adjusting inputs to the system to regeneration rates, ii) adjusting outputs from the system to absorption rates, iii) closing the system, iv) maintaining the value of resources within the system, v) reducing the system's size, vi) designing for CE, and vii) educating for CE. It is important to emphasize the role of design and education as transversal elements. A new definition and a new conceptual model of CE are also proposed.

Contents

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1. Introduction

Sustained economic growth based on a linear production model is not feasible in a planet with finite resources and a limited capacity to absorb wastes (Bonciu, 2014). Despite efforts to address the *ecological question* since the 60's, pressures on the global environment have been constantly growing (Valdivielso, 2008), and even some planetary boundaries have been already exceeded (Rockström et al., 2009; Steffen et al., 2015). In this context, circular economy (CE) is regarded as an alternative which may give rise to economic and ecological benefits (EC, 2014).

The CE concept is not new (Winans et al., 2017). However, during the past decade, CE has aroused the interest of companies (Murray et al., 2017) and policy-makers (Brennan et al., 2015), especially in Europe and China. In Europe, the Directive 2008/98/EC on waste introduces the circular economy package (EC, 2015b) and broadens the legislation about recycling and reusing (He et al., 2013; EEA, 2016). In China, CE has been considered as the national development model since 2008 (CCICED, 2008). China's Circular Economy Promotion Law understands CE as reducing, reusing and recycling in production, circulation and consumption (Sakai et al., 2011). Currently, experiments in all levels of implementation are being developed throughout the country (Geng and Doberstein, 2008). Technological advances, design and recovery processes allowed companies to elaborate realistic CE strategies within the industrial ecology framework (Hobson, 2016), encouraging reduction of raw material use and waste production, which is translated into environmental and economic benefits for companies (Andersen, 2007). Indeed, one of the main causes of the expansion of the CE concept is its ability to connect strategies from different schools of thought (Matus et al., 2012) —such as cradle to cradle design (Braungart et al., 2007), zero waste (Pauli, 2010) or cleaner production (de Jesus et al., 2016), among others—, thereby stimulating the scientific exploration of the CE paradigm (Elia et al., 2017).

The scientific literature about CE is scarce and both conceptual discussions and the design of practical strategies of implementation are still emerging (Korhonen et al., 2018a). Certainly, there is still not a consensus on the theoretical framework of CE (Kirchherr et al., 2018; Prieto-Sandoval et al., 2018). Some authors discuss the role of CE within sustainable development and its goals and consider social objectives for CE within sustainable development (e.g. Kirchherr et al., 2017; Murray et al., 2017). Others, by contrast, only claim economic and ecological goals for CE (e.g. Sauvé et al., 2016; Geissdoerfer et al., 2017). These investigations are considered as part of the CE theoretical paradigm (Korhonen et al., 2018a), where theoretical strategies are also discussed. Whereas theoretical strategies refer to the economic system, practical strategies refer to the actions that should be carried out to implement a CE system. Within the CE practical paradigm (Korhonen et al., 2018a), several investigations analysed different practical strategies for its implementation (e.g. Elia et al., 2017; Kalmykova et al., 2018) and proposed suitable indicators to measure its performance (e.g. Herva et al., 2011; Geng et al., 2012; Park and Chertow, 2014; Di Maio and Rem, 2015; Ellen MacArthur Foundation, 2015a; Elia et al., 2017).

The significant disparity between theoretical approaches to the CE concept (Bocken et al., 2016) hinders a consensus around the definition of a widely accepted theoretical framework on which the development of strategies and the implementation of CE systems could be founded (Kalmykova et al., 2018; Korhonen et al., 2018b). In addition, investigations focused on theoretical aspects and on the practical paradigm are very poorly connected (Sauvé et al., 2016). Despite the fact that CE systems are currently being implemented (Geng and Doberstein, 2008), CE goals and principles need to be better considered and translated into actions (Pauliuk, 2018), and more coordinated actions among different levels of implementation are clearly required (McDowall et al., 2017).

In this research we conduct a review of the scientific literature relative to CE and propose operational principles which could connect the theoretical goals of CE within the sustainable development framework to practical strategies of implementation. Thus, a communication channel between theoretical and practical realms of CE would be created. To achieve our aim, the role of CE under the sustainable development framework, the goals of CE within this framework and the classification of practical strategies of CE based on the proposed operational principles are discussed.

2. Material and methods

A literature review was conducted in two phases from January 2018 to July 2018. Firstly, the keywords ‘circular economy’ and ‘sustainable development’ were used to search for papers in the Web of Science database. Subsequently, the ‘snowball’ technique was applied. Snowballing “refers to using the reference list of a paper or the citations to the paper to identify additional papers”, what “could benefit from not only looking at the reference lists and citations, but to complement it with a systematic way of looking at where papers are actually referenced and where papers are cited” (Wohlin, 2014). As a result, a total of 68 scientific papers were found and analyzed, as well as several books and reports published by public and private institutions.

Table 1 shows the origin of the papers used in this study. The most important journal in this research is *Journal of Cleaner Production* with 19 papers, followed by *Resource, Conservation and Recycling*, *Journal of Industrial Ecology* and *Ecological Economics* with 4 papers each. Scientific reports mainly arise from the Ellen MacArthur Foundation, a pioneering organization within the CE framework (e.g. Ellen MacArthur Foundation, 2013, 2015a, 2017), and the European Union Institutions, that are currently working on the implementation of the Circular Economy Action Plan (e.g. EC, 2015a, 2015b; 2018). The Chinese Circular Economy Promotion Law of the People's Republic of China (CCICED, 2008) is also an essential document considered in this research.

The temporal evolution of the number of papers used in this study published each year (Fig. 1) shows that CE is a novel concept within the scientific field, as most of the papers used in this research were published after 2006.

3. Theoretical framework

The CE concept has not reached a mainstream yet (Kirchherr et al., 2018). The literature review and the analysis of definitions shown in Table 2, found three common theoretical strategies under the CE paradigm: i) minimizing inputs of raw materials and outputs of waste ii) keeping resource value as long as possible within the system, and iii) reintegrating products into the system when they reach the end-of-life (e.g. Ghisellini et al., 2016; Elia et al., 2017; Kalmykova et al., 2018).

Several questions remain still unsolved: what is the relationship between CE and sustainable development? (Geissdoerfer et al., 2017). Based on this relationship, what are the targets of CE? (Kirchherr et al., 2017). With regard to the theoretical and practical strategies within the CE framework, what is the role of 3R (Reduce, Reuse and Recycle), eco-design, eco-innovation (de Jesus et al., 2016), consumption (Kirchherr et al., 2018) and education in CE? (De los Rios and Charnley, 2017). All these issues are discussed in section 4.

There is a scientific consensus, however, about the existence of three implementation levels of CE: micro level, meso level and

Table 1
Publications on CE by journal title resulting from the literature review carried out in this study.

Source	Count	Percent
Journal of Cleaner Production	19	28%
Resources, Conservation and Recycling	4	6%
Journal of Industrial Ecology	4	6%
Ecological Economics	4	6%
International Journal of Sustainable Development & World Ecology	3	4%
Science	3	4%
Sustainability Science	2	3%
Sustainability	2	3%
Journal of Business Ethics	2	3%
Global Environmental Change	2	3%
Journal of Environmental Management	2	3%
Once-cited journals	21	31%
Total	**68**	**100%**

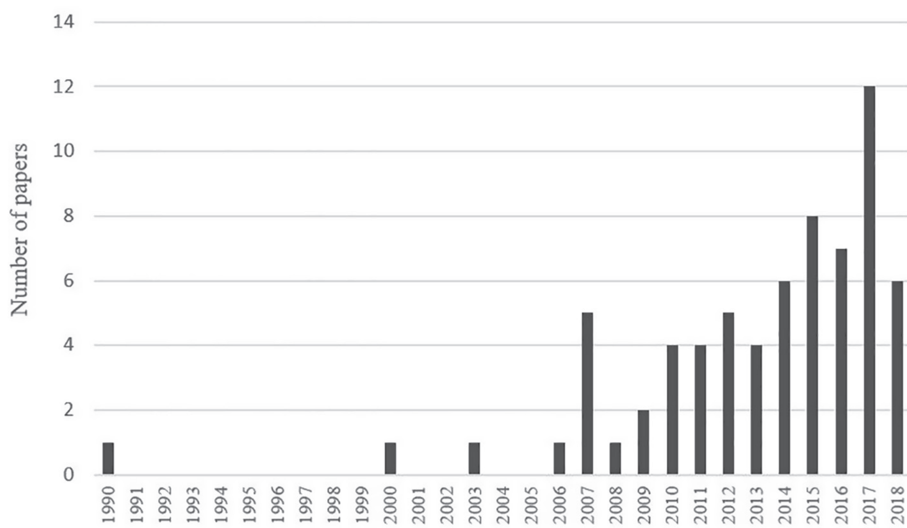

Fig. 1. Number of papers used in this investigation published each year.

Table 2
Explicit definitions of Circular Economy.

Definitions	References
Circular Economy systems keep the added value in products for as long as possible and eliminates waste. They keep resources within the economy when a product has reached the end of its life, so that they can be productively used again and again and hence create further value	*EC (2014, 2015)*
The circular economy is one that is restorative and regenerative by design and aims to keep products, components, and materials at their highest utility and value at all times, distinguishing between technical and biological cycles. This new economic model seeks to ultimately decouple global economic development from finite resource consumption. It enables key policy objectives such as generating economic growth, creating jobs, and reducing environmental impacts, including carbon emissions.	*Ellen MacArthur Foundation (2015b)*
Model of production and consumption of goods through closed loop material flows that internalize environmental externalities linked to virgin resource extraction and the generation of waste (including pollution)	Sauvé et al. (2016)
We define the Circular Economy as a regenerative system in which resource input and waste, emission, and energy leakage are minimised by slowing, closing, and narrowing material and energy loops. This can be achieved through long-lasting design, maintenance, repair, reuse, remanufacturing, refurbishing, and recycling	Geissdoerfer et al. (2017)
The Circular Economy is an economic model wherein planning, resourcing, procurement, production and reprocessing are designed and managed, as both process and output, to maximize ecosystem functioning and human well-being	Murray et al. (2017)
A circular economy describes an economic system that is based on business models which replace the 'end-of-life' concept with reducing, alternatively reusing, recycling and recovering materials in production/distribution and consumption processes, thus operational at the micro level (products, companies, consumers), meso level (eco-industrial parks) and macro level (city, region, nation and beyond), with the aim to accomplish sustainable development, which implies creating environmental quality, economic prosperity and social equity, to the benefit of current and future generations	Kirchherr et al. (2017)
Circular Economy is a sustainable development initiative with the objective of reducing the societal production-consumption systems' linear material and energy throughput flows by applying materials cycles, renewable and cascade-type energy flows to the linear system. Circular economy promotes high value material cycles alongside more traditional recycling and develops systems approaches to the cooperation of producers, consumers and other societal actors in sustainable development work	Korhonen *et al.* (2018a)

macro level (Elia et al., 2017; Korhonen et al., 2018a). The micro level refers to the implementation of CE systems in a company (Franco, 2017). At this level, well established ideas from different schools of thought, such as *Cleaner production* or *Industrial ecology*, are integrated (Brown and Stone, 2007; Bilitewski, 2012). The meso level refers to the interaction within the inter-firm network (Zhu et al., 2010), a network that does not normally need to be within the 'park boundaries' and which may lead to industrial symbiosis (Chertow, 2000). The macro level refers to the implementation of CE systems in the society as a whole, i.e. cities, regions, nations and the international community (de Jesus et al., 2016). At this level, legislation is the main instrument to be considered (Feng and Yan, 2007). Moreover, concepts such as urban symbiosis, eco-cities, collaborative consumption models, innovation waste management and zero waste programmes, among others, can be considered as part of this level of implementation (Ghisellini et al., 2016).

3.1. Research approach

In this research, CE is analyzed under the sustainable development framework, a widely spread approach among scholars (e.g. Geng and Doberstein, 2008; Sauvé et al., 2016; Geissdoerfer et al., 2017; Kirchherr et al., 2017). A top-down discussion is conducted throughout section 4. Firstly, the relationship between CE and sustainable development is discussed, and the intersection between them is defined (section 4.1). Based on this relationship, CE goals under the sustainable development framework are identified (section 4.2) and seven operational principles are proposed (section 4.3). Finally, a new definition and a new conceptual model of CE are also proposed (section 5).

4. Results

4.1. Relationship between sustainability and circular economy

Sustainable development is very frequently defined as 'development that meets the needs of the present without compromising the ability of future generations to meet their own needs' (WCED, 1987). Based on this declaration, two different ways of addressing sustainability emerged. While *strong sustainability* suggests that natural capital cannot be replaced by human capital, *weak sustainability* claims for the possibility of substituting natural by human capital (Andersen, 2007). Nevertheless, both approaches raise the existence of ultimate ecological limits, something that is also expressed in the report of the Brundtland commission: 'ultimate limits there are […] At a minimum, sustainable development must not endanger the natural systems that support life on Earth: the atmosphere, the waters, the soils, and the living beings' (WCED, 1987).

CE seems to incorporate some notion of justice in resource utilization among generations which is implicit in the sustainable development concept (Xia and Yang, 2007; Geissdoerfer et al., 2017). Indeed, most of scholars accept the close relationship that exists between both concepts (Geissdoerfer et al., 2017). However, the role of CE under the sustainable development framework still remains unclear.

Two clearly different positions were identified by Sauvé et al. (2016). On the one hand, some experts "perceive sustainable development as a set of initiatives that have been implemented within a linear thinking", while CE "offers a solution where sustainable development […] is perceived as a failure". On the other hand, most authors presented sustainable development and circular economy as coherent disciplines and even interdependent, i.e. "circular economy becomes a tool for sustainable development". Later, Geissdoerfer et al. (2017) extended the review of Sauvé et al. (2016) and supported that there is a clear relationship between both concepts articulated around three different possible connections: i) CE is necessary for sustainable development, ii) CE is beneficial to sustainable development, and iii) CE and sustainable development have a compensatory relationship. We, therefore, conclude that: i) there is a close relationship between both sustainable development and CE and ii) CE is at least beneficial to achieve sustainable development. Moreover, Genovese et al. (2017) defended that a bottom-up movement towards sustainable development is needed and Bonciu (2014) suggested that sustainable development addresses the current problems but not the causes, what CE does. In other words, sustainable development establishes goals to be achieved in order to solve the problems and their consequences, whereas CE is a tool to address some of the causes of these problems.

One of the topics currently under debate is centered on the dimensions of sustainable development actually covered by CE. In this connection, Sauvé et al. (2016) show that most scientific literature supports that CE has economic and ecological targets, but not social targets. According to this author, CE would be located in the conceptual space defined in Fig. 2 in the interphase between the ecological and the economic dimensions of sustainability (areas 1 and 2). By contrast, Murray et al. (2017) and Kirchherr et al. (2017) suggested the introduction of the social dimension into the CE paradigm. In our view, if CE is understood as a tool to reach targets of sustainable development, a transference of a certain responsibility of social targets to CE is inevitable and the achievement of social goals results inherent to the consecution of ecological and economical aims (Birat, 2015). Consequently, CE might be placed in the intersection between the ecological, economic and social dimensions of sustainability (area 2) in Fig. 2, an expected result considering that we are studying CE under the sustainable development framework.

4.2. The goals of circular economy

The implementation of CE systems has thermodynamic limits that constrain the cost of converting linear into circular material flows (Korhonen et al., 2018b), so loops should be supported only when they are socially desirable and efficient (Andersen, 2007). To assess the balance between benefits and costs associated with these loops, the establishment of goals is required.

The goal of decoupling economic growth or economic development from utilization of finite resources is recurrent in the

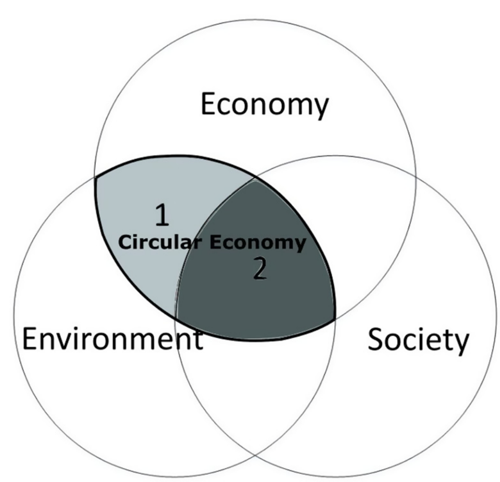

Fig. 2. Relationship between circular economy and sustainable development.

reviewed literature (e.g. EC, 2014; Ellen MacArthur Foundation, 2015b; Ghisellini et al., 2016; Korhonen et al., 2018b). Nevertheless, given that CE goals are considered to emanate from sustainable development targets, it is necessary to distinguish between two types of inputs: renewable and non-renewable resources. Regarding renewable resources, the operational criteria of Daly (1990) for sustainable development are used to establish a semi-quantitative target: the extraction rate of renewable resources has to be lower than the regeneration rate of those resources. The scientific responsibility of converting these extraction rates into measurable values is located within the Planetary Boundary Framework (Rockström et al., 2009; Steffen et al., 2015), that delimits the safe operational space for human activities within the planet (Heck et al., 2018) and that is currently in constant development (e.g. Gerten et al., 2013; Mace et al., 2014; Liu et al., 2015; Newbold et al., 2016; Nash et al., 2017).

Non-renewable resources are depleting resources by definition. Therefore, in order to reach sustainability, the exploitation rate of non-renewable resources should be lower than the creation rate of renewable substitutes (Daly, 1990), what would allow the supply of enough renewable resources even when non-renewable resources had disappeared completely. In this context, Turner (1988) presented a less restrictive condition that urges the consumption of non-renewable resources to be as slow as possible, and preferably consuming renewable resources. Either way, the consumption of non-renewable resources needs to be minimized as much as possible, or even it should be eliminated.

The aim of minimizing wastes has been also identified (e.g. EC, 2014; Ellen MacArthur Foundation, 2015b; Haas et al., 2015; de Jesus et al., 2016; Kalmykova et al., 2018). In this regard, it is important to distinguish between two types of outputs: biological wastes and technical wastes (Ellen MacArthur Foundation, 2015b). Biological wastes are biodegradable compounds flowing through biogeochemical cycles that will eventually be reconverted into natural capital. According to the operational criteria proposed by Daly (1990), the emission rates of biological wastes has to be lower than the natural capacity of ecosystems to assimilate the released wastes. By contrast, technological wastes are not biodegradable, what means that they require a process of human transformation in order to be reincorporated into the economic system. Consequently, technical wastes need to be minimized, or even eliminated (Riechmann et al., 1995), a conclusion that can be also drawn from the conceptual model for CE described by Ellen MacArthur Fundation (2015b).

Fig. 3 represents the relationship between the economic system and the biosphere in accordance with Daly (1990) and the Global Footprint Network (2012). In the past, the linear economy system's size remained within the biosphere's size (Fig. 3 a). Currently, the linear economy system exceeds the capacity of resource extraction and wastes and emissions absorption of the planet (Fig. 3 b). The aim of the CE under the sustainable development framework should be reducing the economic system's size until acceptable proportions for the biosphere (Fig. 3 c). Thus, we suggest that: *the aim of the CE under the sustainable development framework should be to decouple economic development from the utilization of finite resources and wastes and emissions generation, by maintaining extraction rates of resources and generation rates of wastes and emissions under suitable values for planetary boundaries.*

4.3. Operational principles of circular economy

According to the Cambridge dictionary, a principle is *'a basic idea or rule that explains or controls how something happens or works'* and an operational principle can be defined as *'the essential characterization of how the device works'* (Vincenti, 1990). An operational principle defines how the parts interact with one another in order to implement the goal of overall technology (Frenken, 2006).

Therefore, we use the term operational principles to describe theoretical strategies that explain how CE systems operate. They allow the achievement of established goals and, at the same time, they are necessarily connected to the practical implementation strategies. In this section, theoretical strategies related to the CE concept are discussed and a simplification to seven operational principles is proposed: two target operational principles, three core operational principles and two transversal operational principles.

This classification has been performed based on the main objective of each practical strategy of implementation. For instance, improving energy efficiency mainly aims to reduce the total amount of resources used to produce a certain amount of energy, what allows adjusting the extraction rate of resources to the biosphere's natural regeneration rate. Certainly, improving energy efficiency also results indirectly in reducing emissions, but the main objective is reducing inputs to the system. Therefore, even though some strategies reduce both inputs and outputs, they can be classified into one single operational principle in accordance with their main objective.

4.3.1. Target operational principles

Target operational principles emanate directly from the theoretical objectives of CE. They constitute the direct communication channels between theoretical aims of CE and some practical strategies for implementation.

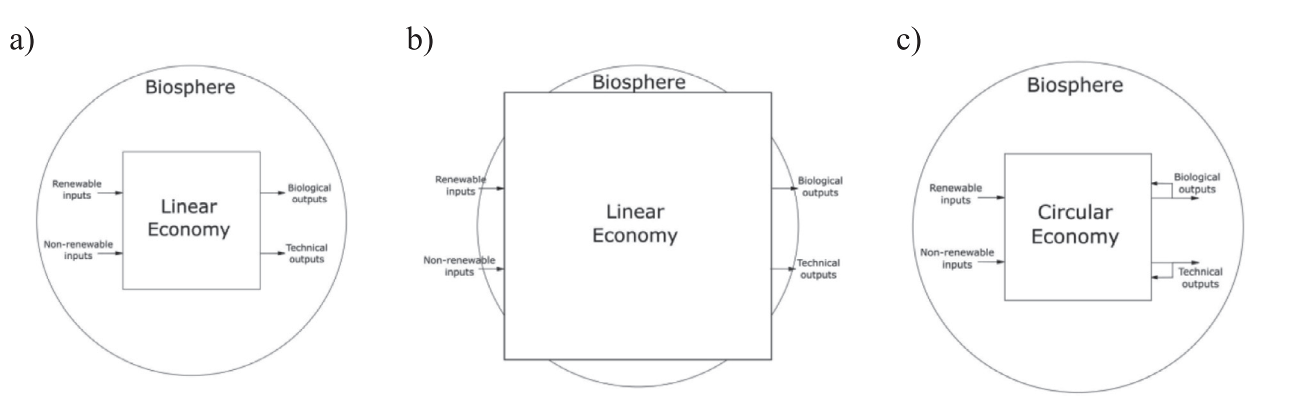

Fig. 3. Relationship between the economic system and the biosphere. Linear economy system was feasible in the past (a). Currently, the linear economy system's size is bigger than the biosphere's size in terms of consumption and extraction rates (b). Circular economy aims to adjust these rates to planetary boundaries again (c).

4.3.1.1. Operational principle 1: adjusting inputs to the system to regeneration rates. To address the adjustment of inputs into the system to regeneration rates, distinguishing between renewable and non-renewable resources becomes essential. This operational principle concerns with strategies that minimize – and even eliminate – the inputs of non-renewable resources and adjust the extraction rate of renewable resources to suitable values for planetary boundaries. Elia et al. (2017) suggested that reducing inputs should be monitored within the CE paradigm. One of the most common strategies reported in the scientific literature is based on improving eco-efficiency (EC, 2014, 2015b), i.e. increasing efficiency during the production and the consumption process (Su et al., 2013), which results in the isolation of the economic dimension and the social welfare from the ecological dimension (Ness, 2010) by consuming less resources per unit of produced value (Figge et al., 2014). Moreover, promoting the use of renewable energies is considered as a key point for CE (Ellen MacArthur Foundation, 2013; Elia et al., 2017). The transition towards renewable energies is an essential strategy to reduce inputs to the system which usually produce negative externalities. In addition, other strategies related with dematerialization are also encompassed by this operational principle (Elia et al., 2017; Kalmykova et al., 2018).

4.3.1.2. Operational principle 2: adjusting outputs from the system to absorption rates. The discussion on adjusting outputs from the system to absorption rates also requires distinguishing between technological and biological outputs. This operational principle promotes strategies that minimize, and eliminate, the outputs of technological wastes and adjust the emission rate of biological wastes to suitable values for planetary boundaries. Elia et al. (2017) also suggest that reducing outputs should be monitored within the CE paradigm. Eco-efficiency becomes again an important strategy for this operational principle (EC, 2014, 2015b).

4.3.2. Core operational principles

Core operational principles are not directly derived from theoretical objectives, but they are crucial to accomplish them. They characterize the essence of the Circular Economy as a tool. Therefore, these operational principles are able to channel strategies that indirectly adjust inputs of resources to the system to regeneration rates and outputs of wastes and emissions from the system to absorption rates.

4.3.2.1. Operational principle 3: closing the system. Closing the system aims at connecting the waste management stage to the resource acquisition stage. Therefore, this operational principle integrates 3R philosophy, an issue widely extended throughout the CE paradigm (e.g. CCICED, 2008; EC, 2015a; Ghisellini et al., 2016; Tisserant et al., 2017). According to the EU (EU, 2008), waste management is hierarchically organized in the following phases: i) prevention, ii) preparing for re-use, iii) recycling, iv) other recovery, i.e. energy recovery, and v) disposal in landfill. Prevention could be placed within the first and second operational principles and, therefore, this operational principle should prioritize reusing and recycling, so that the potential for recycling and reusing of products should be assessed (Park and Chertow, 2014). As products and components which are difficult to reuse and recycle, would still remain, valorisation and energy recovery should be considered whereas landfill should be eliminated as quickly as possible.

Reutilization aims at using again products or components with the same purpose they were conceived (EU, 2008). This has multiple benefits with respect to recycling in terms of energy and resource savings (Castellani et al., 2015). Recycling includes any operation which reprocesses wastes into products, materials or substances, with the same or other purpose they were conceived, and including reprocessing of organic matter (EU, 2008). This would reduce the environmental impact related to resource extraction and waste treatment to be incinerated or sent to landfills (Birat, 2015). Neither energy recovery nor landfill are included within the concept of recycling (EU, 2008).

4.3.2.2. Operational principle 4: maintaining resource value within the system. This operational principle generates a broad consensus in the scientific literature (Korhonen et al., 2018b). Two main strategies have been reported: i) improving durability of products and ii) recirculating resources through the different stages of a product life cycle.

Most scholars support durability as an essential concept (Kalmykova et al., 2018; Korhonen et al., 2018b), and in this regard, the Ellen MacArthur Foundation (2015a) designed an indicator for its quantification. One of the main obstacles to improve durability, especially in electronics, is obsolescence (Guiltinan, 2009).

Interconnecting intermediate stages of a product life cycle is also a recurrent topic in the literature (Elia et al., 2017; Korhonen et al., 2018a). There are different possibilities of connection: reuse, repair, refurbish, remanufacture, recondition and repurpose (e.g. Di Maio and Rem, 2015; van Buren et al., 2016; de Jesus et al., 2016; Kalmykova et al., 2018). Examples of these possibilities are: feedback the consumption process through reparation and repurpose; feedback the production process through industrial symbiosis or by establishing a closed-loop production system through the value chain; or feedback the distribution stage from the consumption stage by selling a product using a web site. The closer the loop, the more efficient and beneficial it is (Stahel, 2013).

4.3.2.3. Operational principle 5: reducing the system's size. The main objective of this operational principle is to reduce the total quantity of resources that circulate within the system, an issue identified in some works as social stock reduction (Haas et al., 2015; Pauliuk, 2018). Two main strategies were identified: i) reducing the total quantity of products required to meet human needs, and ii) producing and consuming more sustainable products, which implies improving the efficiency of the global production-consumption process.

Firstly, individual property of products is presented as one of the current barriers to the successful implementation of circular economy at the global scale, so proposals suggesting a higher reliance on sharing economy and service economy are gaining strength (EESC, 2014; Tukker, 2015). Secondly, informing consumers properly would empower them, so transparency becomes essential in the production side (Tukker, 2015). In the consumption side, some scholars go beyond the Extended Producer Responsibility (Sakai et al., 2011; Manomaivibool and Ho, 2014) and claim for responsibility of each stakeholder, including consumers (Connett et al., 2011), as the implication of consumers could be favourable for producing and selling more sustainable products and services (Geng and Doberstein, 2008; Su et al., 2013).

Furthermore, since the logics from de-growth economy (Kallis et al., 2012; Sekulova et al., 2013) and the steady-state economy (Daly, 2007) are connected to the reduction of system's size, they should be incorporated into the CE paradigm.

4.3.3. Transversal operational principles

Transversal operational principles are needed to promote the success of the rest of operational principles. They are issues that take part, to a greater or a lesser extent, of any CE strategy.

4.3.3.1. Operational principle 6: designing for Circular Economy. There is a total consensus in the scientific literature about the importance of design within the CE framework (Kalmykova et al., 2018; Korhonen et al., 2018a). Design covers multiple perspectives of the CE model. For instance, a product can be designed to be easily recovered and recycled, to be easily repaired or to be easily removable into modules, among other possibilities. These actions take part of the eco-design concept, an essential key to guarantee the success of CE (Sauvé et al., 2016; Elia et al., 2017).

Innovation is also needed in social, organizational, financial or political issues. These necessary actions can be located under the scope of eco-innovation, what according to Kemp and Pearson (2007), is 'the production, assimilation or exploitation of a product, production process, service or management or business method that is novel to the organization (developing or adopting it) and which results, throughout its life cycle, in a reduction of environmental risk, pollution and other negative impacts of resources use (including energy use) compared to relevant alternatives'. Toxopeus et al. (2015) emphasize the idea that innovation is a driving process toward the new paradigm, in contraposition to the simple optimization of processes. Designing for a CE covers fundamental issues to lead the transformation process from a linear production-consumption model into a circular one (de Jesus et al., 2016; Prieto-Sandoval et al., 2018).

4.3.3.2. Operational principle 7: educating for Circular Economy. Education is also a key element to guarantee the success of CE. Article 7 of the Circular Economy Promotion Law of the People's Republic of China declares that 'the state […] encourages the publicity and education of circular economy, the popularization of scientific knowledge and international cooperation in the development of circular economy' and article 10 says that 'citizens shall enhance their awareness of resources conservation and protecting the environment, consume resources in a reasonable way and save resources' (CCICED, 2008).

From the producer perspective, launch of CE strategies requires a variety of values, knowledge and skills that should be integrated (De los Rios and Charnley, 2017). CE does not seek to analyse a product life cycle from a reductionist perspective, but aspires to assess individual products from a holistic vision where the product moves through different connections among processes. This needs a change of paradigm that involves and interconnects every social actors in order to foster collaboration (Ghisellini et al., 2016). Designing a product with comprehensive overview and by collaborating with other industries will just success under the new paradigm, but to make it happens, an improvement of personal and social skills is required (EEA, 2016).

From the consumer perspective, the need to set up a new consumption culture is a widely extended topic within the scientific literature (Geng et al., 2012; SITRA, 2015; Kalmykova et al., 2018). It is known that demanding more sustainable products favours the production of these products (Kirchherr et al., 2018). A new consumption culture that covers necessities and avoid accumulation of properties is needed (Yang et al., 2011; Sauvé et al., 2016). In this connection, it is recognized that our society suffers addiction to growth, and education is a tool to counteract this behaviour (van Griethuysen, 2010).

The success of CE will depend on a change of paradigm (Elia et al., 2017) which should tend to change structural basis of the social and economic activities (Preston, 2012). Naustdalslid (2014) concluded that one of the elements that is currently limiting the expansion of CE systems in China is the lack of social implication and Mihelcic et al. (2003) postulate that education and human resources are required to guarantee the success of CE. Bonciu (2014) concludes that CE implies changing education, values, and behaviour of producers and consumers. In conclusion, education is a transversal issue, which is able to lead to the development and expansion of CE.

4.4. Classification of practical strategies

In order to corroborate the validity of the operational principles, Table 3 presents a non-exhaustive list of practical strategies for the implementation of the seven CE operational principles proposed in this investigation. Most of the strategies have been taken from those reported by Bocken et al. (2016), Elia et al. (2017) and Kalmykova et al. (2018). The operational principles demonstrated to be useful communication channels between the theoretical objectives of CE and the practical strategies of implementation.

5. Definition and conceptual model of circular economy

The analysis carried out in this work led us to propose a new definition and a new conceptual model of CE. The proposed definition is based on the integration of i) the operational principles —in order to cover the enormous diversity of concepts and practical tools under the CE framework—, ii) the three levels of implementation, and iii) the objectives of CE under the sustainable development framework.

Taking these considerations into account, the following definition of CE is proposed: *circular economy is a regenerative production-consumption system that aims to maintain extraction rates of resources and generation rates of wastes and emissions under suitable values for planetary boundaries, through closing the system, reducing its size and maintaining the resource's value as long as possible within the system, mainly leaning on design and education, and with capacity to be implemented at any scale.* This definition explains the operational model of CE, covers the seven operational principles and exposes the capacity of CE to be carried out in any level of implementation.

The new conceptual model proposed should cover the objectives of CE, should be valid for the three levels of implementation, and also should be able to represent the transversal operational principles.

The CE model put forward by the European Commission (2018) presents CE as a system with five processes to be monitored (Elia et al., 2017): i) material input, ii) design, iii) production and delivery, iv) consumption, and v) end of life resource management. From a mathematical point of view this model is far away from usefulness as design is not considered as an underlying concept and inputs and outputs are absent. Moreover, a key element such as education is also absent. In contrast, the level of abstraction makes this model able for the three levels of implementation.

The model proposed by the Ellen MacArthur Foundation (2015c) includes the distinction between the biological and technical cycles. It is useful at the macroscale, but its high level of detail makes it hard to adapt to micro and mesoscales. Furthermore, transversal elements are absent in this model.

In order to overcome the limitations identified in the previous paragraphs, a new conceptual model, derived from this investigation, is proposed (Fig. 4). This model presents nine elements to be monitored: i) inputs, ii) outputs, iii) resources, iv) production, v) distribution and services, vi) consumption, vii) waste management, viii) design, and ix) education. Both renewable and non-renewable inputs and technical and biological outputs are explicit in the model. Non-renewable inputs and technical outputs are represented by dotted lines due to the fact that they should tend to be minimized as much as possible based on the objectives for CE proposed in this work under the sustainable development framework. Each arrow in the diagram represents the possible pathways resources can follow. The arrows that enter and leave the system in Fig. 4 correspond to those represented in Fig. 3C. Therefore, they represent the interaction between the economic system and the biosphere. In the case of the inputs, raw materials are acquired from the biosphere, and converted into resources within the system.

Table 3
Practical strategies of Circular Economy grouped by the proposed operational principles.

Strategies
Principle 1: Adjusting inputs to the system to regeneration rates
Substituting non-renewable by renewable inputs (e.g., bio-based materials, renewable energy)
Substituting renewable materials with low regeneration rates for other with faster regeneration rates
Adjusting taxes and subsidies of technology, products and materials based on their resource regeneration rates
Saving energy and materials (i.e. improving energy efficiency, resource productivity, virtualizing products, etc.)
Fostering renewable mobility (i.e. walking, bicycle, renewable fuels, etc.)
Principle 2: Adjusting outputs from the system to absorption rates
Substituting materials and processes which produce technical outputs by those which produce biological outputs
Substituting processes for those with lower waste generation rates (i.e. more eco-efficiency processes)
Adjusting taxes and subsidies of technology, products and materials based on their waste generation rates
Principle 3: Closing the system
Separating biological and technical wastes properly
Remanufacting products and components
Promoting and improving downcycling, recycling and upcycling of wastes (i.e. logistics, take-back systems, technology, etc.)
Promoting energy recovery by converting waste into heat, electricity or fuel
Promoting Extended Producer Responsibility
Principle 4: Maintaining resource value within the system
Interconnecting stages (i.e. redistributing second-hand goods)
Promoting industrial symbiosis (i.e. establishing standards, cascading, by-products, etc.)
Increasing durability (i.e. practical guides for reparability, preventive and corrective maintenance, repurposing, etc.)
Reducing obsolescence (i.e. updating software)
Principle 5: Reducing the system's size
Informing consumers properly (i.e. eco-labelling, product labelling, product declarations, etc.)
Expanding the Extended Consumer Responsibility
Promoting functional service economy and sharing economy (i.e. collective mobility)
Promoting green procurement (i.e. local products, season products, etc.)
Adjusting selling doses to consumer doses
Principle 6: Designing for circular economy
Eco-design (i.e. optimizing packaging, improving durability, etc.)
Designing transparent, reproducible and scalable products to build the same products in other places based on local resources
Thinking about practical utilities and consumer preferences (customization/made to order)
Designing new business models and strategies
Designing new methodologies to guarantee a continual improvement
Designing projects to promote sustainable development and circular economy
Principle 7: Educating for circular economy
Adjusting educational curricula to the current challenges
Promoting knowledge, skills, capabilities and values that ensure the proper performance of circular economy
Promoting habits and individual actions in favor of circular economy

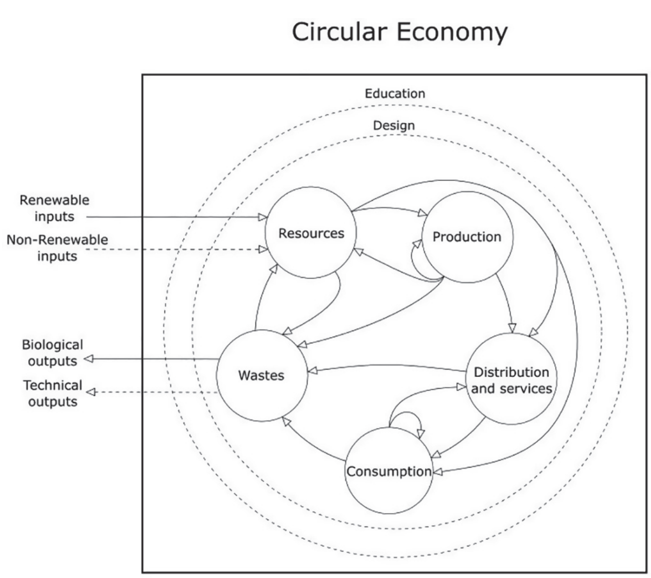

Fig. 4. Conceptual model for circular economy proposed in this study.

Outputs represent wastes and emissions that are eventually released to the biosphere (landfill, pollutant emission, etc.). We thus consider that the direct generation of wastes and emissions in any stage results in the transfer of resources from that specific stage to the waste management stage. Then, the final release of wastes and emissions to the biosphere occurs in the waste management stage.

All operational principles can be applied to this model in the three levels of implementation. The arrow connecting the waste management stage to the resource stage represents the "closing the system" operational principle. Maintaining within the circle is mainly represented by connections among intermediate stages, and durability could be measured by analysing the time a resource spends to reach the waste management stage. Reducing the system's size could be represented by the circles' size of the stages and also by the arrows' size among stages. Finally, transversal operational principles are represented around the proposed circular economy system.

The main advantage of this conceptual model is that the physical connection among the different stages is explicitly drawn. This means that the resource flow – which is represented by arrows– can be quantified. By reconverting design and education to transversal elements, the rest of the production-consumption system can be drawn as a flow of physical resources. Moreover, the representation of inputs to the system and outputs from the system is essential to subsequently assess whether the theoretical goals for EC defined in this work within the sustainable development framework are achieved.

6. Final remarks

In this work seven operational principles are proposed: i)

Adjusting inputs to the system to regeneration rates, ii) adjusting outputs from the system to absorption rates, iii) closing the system, iv) maintaining the value of resources within the system, v) reducing the system's size, vi) designing for CE, and vii) educating for CE. The establishment of these operational principles suggests that decision-making of optimal practical strategies of implementation could be carried out based on objectives raising from operational principles, which at the same time emanate from theoretical targets of CE.

The role of design and education as transversal elements are of particular relevance. Without them, reaching goals of CE under the sustainable development framework would be difficult, when not impossible. Moreover, we highlight that the absence of social goals for CE does not exempt decision-making from social responsibility under the sustainable development framework. Furthermore, there exist social benefits related to the achievement of ecological goals, and issues such as equity, gender equality, access to education and other social goals depend on the social and political will added to the decision-making to ensure the achievement of CE targets.

This work suggests some future research lines within this topic. Firstly, we have identified a lack of a system of indicators that covers the connection between theoretical goals and practical strategies of implementation of CE. Consequently, further research in that direction would be desirable. Secondly, the definition of the proposed conceptual framework would allow deepening into the modelling of the relationship between practical strategies of implementation (changes in the system's inputs) and the achievement of the targets set (changes in the system's outputs). Finally, further refinement of the theoretical framework presented in this paper is needed due to the high potential of CE to address the growing concerns about the sustainability of the planet. Analyzing CE under the sustainable development framework may give CE a useful purpose to optimize efforts of policy-makers, companies and the general society.

Declarations of interest

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