Resources, Conservation & Recycling 135 (2018) 190–201

Contents lists available at ScienceDirect

Resources, Conservation & Recycling

journal homepage: www.elsevier.com/locate/resconrec

Full length article

Circular economy – From review of theories and practices to development of implementation tools

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ARTICLE INFO

Keywords:
Circular economy strategy
Circular economy implementation
Circular economy example
Circular economy development
Green supply chain
Cleaner production
Closed loop
Recycling
Sustainable resource use
Stock optimization
Value maximization
Industrial ecology
Cradle to cradle
Steady-state economy
Performance economy

ABSTRACT

The paper provides an overview of the literature on Circular Economy (CE) theoretical approaches, strategies and implementation cases. After analyzing different CE approaches and the underlying principles the paper then proceeds with the main goal of developing tools for CE implementation. Two tools are presented. The first is a CE Strategies Database, which includes 45 CE strategies that are applicable to different parts of the value chain. The second is a CE Implementation Database, which includes over 100 case studies categorized by *Scope*, *Parts of the Value Chain* that are involved, as well as by the used *Strategy* and *Implementation Level*. An analysis of the state of the art in CE implementation is also included in the paper. One of the observations from the analysis is that while such *Parts of the Value Chain* as Recovery/Recycling and Consumption/Use are prominently featured, others, including Manufacturing and Distribution, are rarely involved in CE. On the other hand, the *Implementation Levels* of the used *Strategies* indicate that many market-ready solutions exist already. The *Scope* of current CE implementation considers selected products, materials and sectors, while system changes to economy are rarely suggested. Finally, the CE monitoring methods and suggestions for future development are also discussed in this paper. The analysis of the theoretical approaches can serve as an introduction to CE concept, while the developed tools can be instrumental for designing new CE cases.

1. Introduction

The topic of circular economy (CE) is high on the political agenda and in particular in Europe (EC, 2014a,b, 2015a), it is expected to promote economic growth by creating new businesses and job opportunities, saving materials' cost, dampening price volatility, improving security of supply while at the same time reducing environmental pressures and impacts. It has been estimated that eco-design, waste prevention and reuse can bring net savings for EU businesses of up to EUR 600 billion, while at the same time reduce greenhouse gas emissions. Moreover, the additional measures to increase resource productivity by 30% by 2030 could boost GDP by nearly 1% and also create 2 million additional jobs (EC, 2014a,b). In the UK, it is has been estimated that a circular economy could help generate 50,000 new jobs and €12 billion of investment (ESA, 2013), while in the Netherlands the potential benefits of a circular economy have been estimated to amount to €7.3 billion a year in market values, leading to 54,000 jobs and numerous environmental benefits (TNO, 2013). Following this prospects, the European Commission (EC) and member states governments are developing agendas, policy documents and investment strategies, which will promote circular economy. Recently, the EC proposed the Action Plan for the promotion of circular economy (EC, 2015b). The Dutch government, together with facilitator stakeholders, is currently executing Realization of Acceleration of a Circular Economy (RACE) project launched in 2014, with the goal of making Netherlands a "circular hotspot".

However, we argue that dissemination of the circular economy is hampered because the CE field is currently populated by diverging approaches. Also, no analysis of the available CE implementation strategies and the CE implementation experience have been developed yet, thus, in particular, precluding effective CE implementation and putting the planned CE investments at risk.

This paper aims to address these two challenges. One of the goals is to contribute with an overview of the CE concept as presented in literature that will assist those actors that wish to work in this field in having a more clear definition of CE. Another goal of this paper is to provide tools for CE implementation. The tools consist of CE Strategies Database, containing available CE-enabling strategies, and CE

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https://doi.org/10.1016/j.resconrec.2017.10.034
Received 6 February 2017; Received in revised form 17 October 2017; Accepted 27 October 2017
Available online 23 November 2017

implementation Database, containing CE case-studies. Among other possible uses, these cross-referenced databases allow finding a suitable CE strategy for designing new CE cases.

This paper has the following structure: Section 2 (Methods) provides details about the method used for literature selection and analysis and the method for construction of the CE Strategies Database and the CE Implementation Database. Section 3 (Results and Discussion) gives a summary of the studied literature (3.1); provides the CE concept overview (3.1.1); presents CE Strategies Database and CE Implementation Database and their possible use scenarios (3.2); and describes the state of the art in the CE implementation (3.3). Section 4 (Conclusions) summarizes this study's main outcomes and their applications.

2. Method

2.1. Literature review

The literature search has been performed during spring 2015 in Scopus database, Google and Google Scholar using "circular economy" as a keyword in the title, keywords or abstract of the document. The search resulted in collection of both academic and non-academic literature (NGOs and companies' reports, policy documents, etc.). Please see Section 2.3 Limitations for description of possible implications of the search boundaries applied in this study.

A screening of the literature has been performed directly during the search by reading the abstracts and discarding the documents where circular economy has not been the main topic. An example of such discarded document was where authors claimed that the described study may contribute to a circular economy, while the main topic has been technical development of a recycling method for a certain material. The selected for the review 118 documents have been categorized into four main categories depending on their content: Theory, Policy, Case Studies and Practice (Table 1). Theory category contains documents discussing the CE concept; Policy category contains legislative and other policy documents; Case Studies contain research and development studies, which have not yet been implemented in the market, e.g. academic studies while the Practice category includes implementations that are already in the market. Different categories of literature have been used towards two goals of this paper. Literature from all the categories has been used to develop the CE Database, literature from the Theory and Policy categories are discussed in the CE concept review, while literature from the Case Studies and Practice categories has been used to develop the CE Implementation Database. References to the reviewed literature, by category, can be found in Table 1. It should be noted, that Table 1 doesn't include fourteen supporting literature documents that describe related to CE concepts, such as: cradle to cradle, performance economy, life-cycle assessment, matter out of space, planetary boundaries, material flow accounting and extended producer responsibility, informal recycling sector challenge in the developing countries. The supporting literature doesn't contain "circular economy" as a keyword and is therefore omitted from the literature review.

2.2. Development of the CE strategies database and the CE implementation database

Strategies for the CE Strategies Database have been collected from all the reviewed literature (see Table 1). The following definition of a strategy has been used for extraction of information from the documents: "a method worked out in advance for achieving some objective, the means or procedure for doing something" (Merriam-Webster, 2017). Definitions for the strategies were composed by the authors based on the descriptions in the original documents or through synthesis of definitions from different sources identified by google search.

Fig. 1, contains a possible CE value chain, where the parts of the value chain are designated by numbers 1–9. The CE value chain is distinguished by a closed loop of material flow and is driven by renewable energy. There are several possibilities for materials to circulate in tight loops. One is a loop through Sharing inside node 5 (Consumption and Use). Other possibilities are through Re-manufacture, Node 8 or through Circular Inputs, Node 9. Circular Inputs are resource inputs or, in general, materials that last for longer than a single lifecycle and can easily be regenerated.

The CE Strategies Toolbox has been arranged in correspondence with the parts of the CE value chain (Fig. 1). The strategies are indexed by two numbers, the first one is the part of the value chain that is addressed and second is the strategy sequence number when the strategies are ordered alphabetically. Such indexing allows easier data handling and cross-referencing. For instance, strategy 1.25 Material Substitution corresponds to Materials Sourcing that is 1st part in the value chain and 25th in the alphabetically ordered strategies list.

The CE implementation cases have been assembled from the literature in the categories Case Studies and Practice in Table 1. For each case study, a suitable strategy from the CE Strategies Database was matched. In the event a strategy used in the case study was missing in the CE Strategies Database, it has been defined and added to the CE Strategies Database. The CE implementation cases have then been systematized into the CE Implementation Database following a new developed classification, see Section 3.2 for details. One of the categories in this classification is the strategy number and name, and another is the part of the value chain. The CE Strategies Database and the CE Implementation Database are therefore cross-referenced through the strategy number/name as well as the addressed part of the value chain.

It should be noted, that no screening has been performed either for the strategies nor the case studies, i.e. all the strategies and all the cases that were found in the reviewed literature are presented. Therefore, no judgment regarding the type of the source (for example internet article, academic paper or an NGO report) or of the case study (what is the agenda behind the case, what is the effect etc.) has been made. Each strategy was assigned to the suitable part of the value chain, unequivocally. Case studies classification is also straightforward: by the Scope of CE (system, sector, product, material or substance) and by Implementation Level (Plan/Policy, R&D or Market Implementation). Within some of the case studies, multiple strategies have been employed. These case studies are reported multiple times, for all the suitable strategies.

The entire population of the case studies has also been used to show a state of the art of CE implementation (the CE Implementation Scene, see Section 3.3 and Fig. 2). The number of case studies for each of the classification categories has been plotted, also indexed by the strategy number employed in each case. In particular, the case studies were plotted regarding the CE Scope – system, sector, product, material or substance, as well as according to the Part of the Value Chain and the Implementation Level (Plan/Policy, R&D or Market Implementation). These plots show a snapshot of the CE implementation within the boundaries of the literature search in this paper and the resulting CE Implementation Scene is therefore not comprehensive.

2.3. Limitations

The literature search has been bounded by the keyword "circular economy" being present in the title, keywords or an abstract of the document. Different terminology may be used for the concepts similar to CE, among them "closed loop economy" and "zero waste economy". In addition, CE appropriates knowledge from several other environmental and engineering fields and suitable strategies and case studies may be contained in documents related to other concepts, such as "green supply chain management", "performance economy", "cradle to cradle", "industrial symbiosis" etc. However, it was chosen not to include similar concepts and other terms possibly used for CE as the keywords for the literature search. This is because branding the content

Table 1
Reviewed literature.

Theory	Policy	Case Studies, academic sources		Practice, business cases
30	17	China, 21	Other geography, 15	36
(Yuan et al., 2006; Zhu, 2006; Andersen, 2007; Di and Chunyou, 2007; Meng and Zhu, 2007; Zhijun and Nailing, 2007; Zhu, 2007; Zhu et al., 2007a; Geng and Doberstein, 2008; Yoshida, 2008; Hislop and Hill, 2011; Mathews and Tan, 2011; Mathews et al. 2011; Geng et al., 2012a; Preston, 2012; Bastein et al., 2013; EMF, 2013; Geng et al. 2013; Su et al. 2013; Bocken et al., 2014; Institute for Environmental Studies, 2014; World Economic Forum, 2014b; World Economic Forum, 2014c; Wu et al. 2014; Yu et al., 2014; George et al., 2015; Kalmykova and Rosado, 2015; Peck et al., 2015; Sauvé et al., 2016; World Economic Forum, 2016)	(EC, 1989; EC, 2000; EMF, 2015a,b; UNEP, 2001; Government of Japan, 2005; EC, 2008; Government of People's Republic of China, 2008; WRF, 2011; Government of Sweden, 2012; OECD, 2012; UNEP, 2012; Dutch Council for the Environment and Infrastructure, 2013; EC, 2014a; EC, 2014b; EEA, 2014; World Economic Forum, 2014a; EC, 2015a; EEA, 2016; WRAP, 2016)	(Yang et al. 2007; Zhu et al., 2007a,b; Ness, 2008; Wang and Geng,2008; Geng et al., 2009; Liujie and Zhu, 2009; Tan et al. 2009; Shi et al., 2010; Xue et al., 2010; Zhu, 2010; Zhu et al. 2010; Hu et al., 2011; Li and Yu, 2011; Zhu et al., 2011; Zhu and Zhao, 2011; Geng et al., 2012b; Pauliuk et al., 2012; Wang et al., 2013; Zhu et al., 2013; Wen and Meng 2015; Yu et al., 2015)	(Genovese et al., 2017; Allwood et al., 2011; Reh 2013; Amouroux et al. 2014; Clouth and Wright 2014; Jodejko-Pietruczuk and Plewa 2014; Lee et al. 2014; Lehmann et al. 2014; Manomaivibool and Hong 2014; Modaresi et al. 2014; Scholz and Roy (2014); Patricio et al. 2015; Riding et al. 2015; Smol et al. 2015; Wijkman and Skånberg, 2015)	(Ecoinvent, 2015; EMF, 2014; Vodafone Ehrenfeld and Gertler, 1997; UNEP, 2001; Cisco, 2006; MBDC, 2008; Bio Intelligence, 2010; DSM 2010; Van Gansewinkel Group, 2011a; Van Gansewinkel Group, 2011b; WRF 2011; Colruyt Group, 2012; Novozymes 2012; Bastein et al. 2013; ESA, 2013; Resource Futures, 2013; PWC 2013; Rossi et al., 2013; Spatuzza, 2013; Su et al. 2013; The Council for the Environment and Infrastructure 2013; Veolia, 2013; WMW, 2013; Accenture Strategy LLP 2014; DSM 2014; European Bioplastics 2014; Michelin, 2014; Novozymes 2014; Institute for Environmental Studies 2014; Suez Environment, 2014; World Economic Forum, 2014b; BMUB, 2015; Repair Cafe, 2015; Desso, 2015; EC 2015b; Google, 2015; MBDC 2015; Nutrient Platform NL, 2015; PowerParasol, 2015; Rabobank, 2015; Renault, 2015; Statoil, 2015; Tarkett, 2015; Chiho-Tiande Group, 2016; ESPP, 2016; Google, 2016 Unilever, 2016)

of the literature found with other keywords as "circular economy" content could be questionable (could be disputed by different authors) or even produce misleading results. The reason is that there is no commonly accepted definition of CE nor the criteria for classifying the cases as CE, while all the above concepts have differences with CE. Limiting the literature search to the one in which authors choose to explicitly mention CE ensures that only relevant content has been included and prevents subjective attribution of the content as CE related. The resulting review gives a first order of approximation of the state of the art in the CE field. Using only CE term, the developed CE Strategies Database and the CE Implementation Database are not comprehensive catalogues. Instead, they suggest a structure for classifying and describing CE cases as well as the possible use scenarios and provide a first edition of such catalogues that can be further extended.

3. Results and discussion

3.1. Literature review

Table 1 provides a distribution of used sources including academic papers as well as reports from industry, government, facilitators of sustainable development, NGOs etc. Among the academic sources there is a predominance of the CE case studies, as well as a few theoretical studies describing development in China (Table 1). This is due to the early adoption (year 2002) of circular economy as the nationwide development strategy in China. The expectation was that this strategy would promote sustainable urban development in China and establish an equilibrium between the countryside and urban areas. In particular, waste elimination and reallocation of resources were regarded as good strategies for encouraging rural populations to remain in rural areas. This approach was later supported by the 2003 Cleaner Production Promotion Law, which in 2005 was amended to the "Law on Pollution Prevention and Control of Solid Waste". Viewed as a pioneering legislation of its kind, the CE Promotion Law was implemented in 2009. The law aims to promote economic growth that at the same time does not lead to the material or energy shortage. In a study on CE strategy in China, Yuan et al. (2006) explain that the goal is to achieve the closed loops of energy and material cycles observed in countries like Germany and Sweden. The circular economy in China was to be implemented at 3 function levels: individual businesses, eco-industrial parks and eco-cities/municipalities. As a result of Chinese effort to implement a CE, a body of experience can be found in the sources on Chinese development, in particular in relation to: the implementation of a circular economy as a new economic development strategy (Yuan et al., 2006; Geng and Doberstein, 2008; Xue et al., 2010; Mathews and Tan, 2011; Mathews et al., 2011; Geng et al., 2013; Su et al., 2013; Wu et al., 2014), including regional studies (Yang et al., 2007; Wang and Geng, 2008; Geng et al., 2009); CE implementation in certain economic sectors, such as mining (Geng et al., 2012a), steel industry (Pauliuk et al., 2012; Wang et al., 2013), agriculture (Zhu et al., 2013) and others (Hu et al., 2011; Wen and Meng, 2015).

The experience of CE implementation in China can be suitable to be replicated in other countries. For example, similarly to China, in many other countries the CE development is also top-down, ushered by the governmental initiatives. On the other hand, due to certain local conditions, the challenges in the developed and developing countries are different. For example, in the developing countries and also in China, the informal collection and recycling sector is substantial. The CE policies in these countries are aimed at streamlining the waste and secondary materials flow through the fficial channels only, including bans on informal recycling (Gu et al., 2016; Williams et al., 2013). On the other hand, in the developed countries there are examples of the government initiatives to decentralize recycling. For example in Sweden, promotion of the reuse and repair centers as well as tax breaks for the repair shops have been suggested.

In contrast to the case-studies sources, the CE policy development sources are primarily from Europe, as well as from global organizations

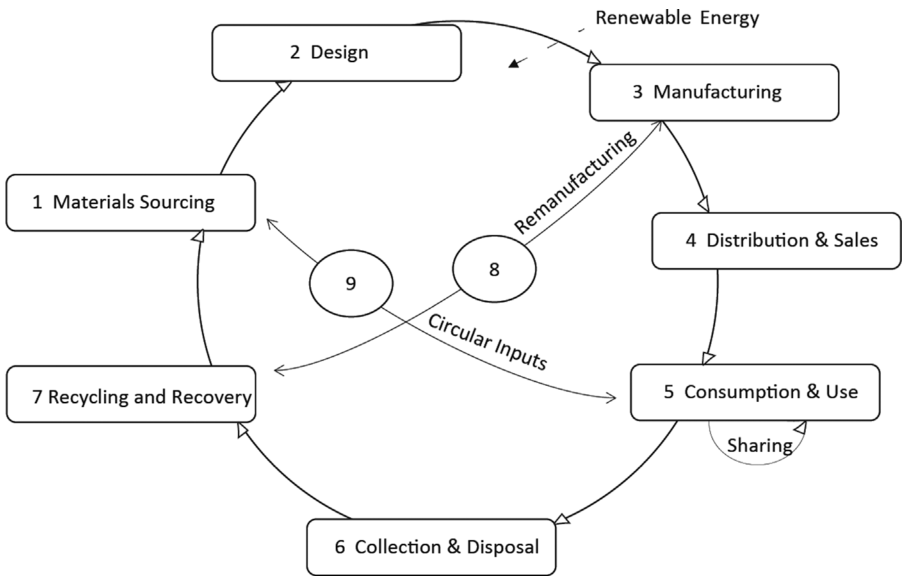

Fig. 1. Resource flows through a value chain in a circular economy. The numbers denote codes for parts of the value chain in Table 2. CE Strategies Database.

and consulting firms. They include scoping, vision/agenda and planning reports from legislative bodies such as the European Commission (EC, 2014a,b, 2015a,b; EEA, 2014) and other authorities (Government of Japan, 2005; Government of Sweden, 2012; OECD, 2012; UNEP, 2012; Dutch Council for the Environment and Infrastructure, 2013); NGOs, such as the Ellen MacArthur Foundation (EMF, 2013, 2015a,b; Institute for the Environmental Studies, 2014), the World Economic Forum (World Economic Forum, 2014a), WRAP (WRAP, 2016) and the Club of Rome (Wijkman and Skånberg, 2015); consulting firms Accenture (Accenture Strategy LLP, 2014) and McDonough Braungart Design Chemistry (MBDC, 2015). The common features of these reports are the acknowledgement of the central role of CE in future economic development, investigation of CE potential for different types of economies, including economic and social (employment) gains, identification of the prioritized sectors for CE implementation; and examples of CE implementation at company level. The recent developments of CE policy can be found in the two Ellen McArthur Foundation reports. The first report, "Growth within: a circular economy vision for a competitive Europe" (EMF, 2015a), puts forward the ReSOLVE framework based on six business actions for businesses and countries wanting to move towards the circular economy: Regenerate, Share, Optimise, Loop, Virtualise, and Exchange. The framework is then used to prioritize 20 major economic sectors in EU for different ReSOLVE actions. The business actions application has been modelled for three human needs – mobility, food, and shelter, in order to define whether these actions could be cost competitive. In this paper, examples of concrete implementation strategies suitable for each of the ReSOLVE actions are given in Chapter 3.3, CE Strategies Database and

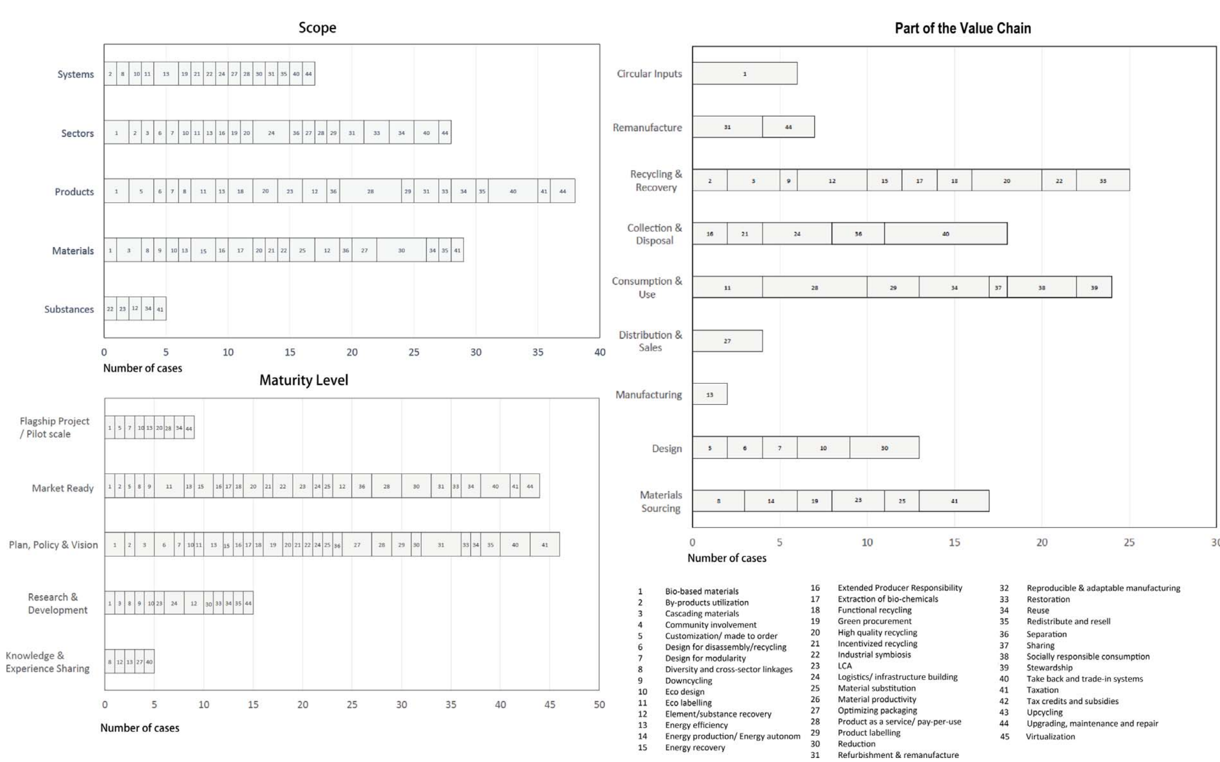

Fig. 2. Analysis of the circular economy Implementation Scene.

CE Implementation Database. The second report, "Delivering the circular economy: a toolkit for policymakers" (EMF, 2015b), provides a step-by-step methodology for the level of the policymakers to accelerate the transition towards the circular economy. At first, the local context of circularity is examined and the scope and level of ambition for CE is established. Next steps include selecting the focus sectors and identifying for them: the CE opportunities and their sector-specific economic impacts, barriers limiting their realization and policy options to overcome these barriers. Then the sector-specific impact assessments are aggregated in one overarching whole-economy impact assessment to support the mandate for policy intervention. Finally, stakeholders are engaged to implement the proposed agenda. In relation to this methodology, the tools developed in this paper, CE Strategies Database and CE Implementation Database, can be used as databases of CE opportunities for different sectors.

3.1.1. CE concept overview

The CE notion draws on many other concepts, established decades ago, such as spaceman economy (Boulding 1966), limits to growth (Meadows, Meadows et al., 1972), steady-state economy (Daly 2005), performance economy (Stahel, 2010), industrial ecology (Frosch and Gallopoulos, 1989) and "cradle-to-cradle" (Stahel and Reday-Mulvey, 1981), among others. However, the interest in the development of the CE concept worldwide has been renewed only recently, which is reflected in the main sources of information on circular economy. In particular, before 2012 "circular economy" have primarily been investigated in the papers describing development in China, due to its early adoption of circular economy as a nationwide strategy (Table 1).Process of CE concept development is currently happening in Europe, which is reflected in the fact that the majority of the relevant literature is published in the form of scope documents and initiatives from governments and NGOs. These publications consider concept formation, vision creation and formulation of strategies. The following definitions of CE have been found in the literature:

1. an industrial economy in which material flows keep circulating at a high rate without entering the biosphere unless they are biological nutrients (EMF, 2012); an industrial economy that is restorative by intention; aims to rely on renewable energy; minimizes, tracks and eliminates the use of toxic chemicals; and eradicates waste through careful design (EMF, 2013); an economy that provides multiple value-creation mechanisms which are decoupled from the consumption of finite resources; in a circular economy, growth comes from 'within', by increasing the value derived from existing economic structures, products and materials (EMF, 2015a,b).

1. focuses on stock optimization. Has a structure of three loops: reuse and re-marketing for goods, product-life extensions for goods and a recycling loop for molecules (secondary resources) (Stahel, 2013);
2. a general term for reducing, reusing and recycling activities conducted in the process of production, circulation and consumption (Government of People's Republic of China, 2008).
3. in the circular economy the value of products, materials and resources is maintained in the economy for as long as possible, and the generation of waste minimized (EC, 2015a,b)
4. an alternative to a traditional linear economy (make, use, dispose) in which we keep resources in use for as long as possible, extract the maximum value from them whilst in use, then recover and regenerate products and materials at the end of each service life (WRAP, 2016).
5. an economic and industrial system based on the reusability of products and raw materials, and the restorative capacity of natural resources, which also attempts to minimize value destruction in the overall system and to maximize value creation in each link in the system (Bastein et al., 2013).
6. an industrial model that decouples revenues from material input (World Economic Forum, 2014b).
7. an industrial system that is restorative by intention and design. The idea is that rather than discarding products before the value are fully utilized, we should use and re-use them (Wijkman and Skånberg, 2015).

It should be noted that the list above is not exhaustive, and other definitions of CE may exist in the non-reviewed literature. The literature that presented definitions 1–8 has been analyzed in order to identify commonalties and differences among the corresponding approaches. One of the common principles found among the approaches is maximizing the value of the resources in use that can also be defined as "stock optimization". This principle has, for example, been expressed in the listed above references as following: ".. increasing the value derived from existing economic structures, products and materials" (EMF, 2015a,b), ".. focuses on stock optimization. '(Stahel, 2013), ".. the value of products, materials and resources is maintained in the economy for as long as possible' (EC, 2015a,b), '.. keep resources in use for as long as possible, extract the maximum value from them whilst in use' (WRAP, 2016), ".. maximize value creation in each link in the system" (Bastein et al., 2013), ".. rather than discarding products before the value are fully utilized, we should use and re-use them (Wijkman and Skånberg, 2015).

The origin of the stock optimization principle is based on the recognition of the limited nature of Earth's resources and can be traced to several well-established concepts including:

- the 'spaceman' economy, which suggested replacing the conventional open economic system with a cyclical system capable of continuous reproduction of materials, even though it cannot exist without inputs of energy (Boulding 1966);
- the "steady-state economy": "an economy with constant stocks of people and artifacts, maintained at some desired, sufficient levels by low rates of maintenance throughput, that is, by the lowest feasible flows of matter and energy from the first stage of production to the last stage of consumption." (Daly, Herman E. 1992);
- the 'limits to growth': the computer simulation of exponential economic and population growth with finite resource supplies under 3 scenarios, two of them leading to "overshoot and collapse" of the global system, while a third to a "stabilized world."
- the 'industrial ecology' that envisions integration of industrial ecosystems in analogy to biological ecosystems (Frosch and Gallopoulos, 1989), with implementation of such biological imitation as an eco-industrial park where materials are recycled internally and where energy is the only external input (Ayres, 1996)
- the "cradle-to-cradle" concept depicts a closed system of resource flows approached from a product-life cycle perspective (Stahel and Reday-Mulvey, 1981).

Another common principle that has been identified in the CE approaches is the Eco-efficiency. It appears in a different way depending on the approach. Some of the approaches stress eco-efficiency as the purpose of CE (Stahel, 2013) or even synonymous to CE (Wijkman and Skånberg, 2015). Other approaches consider eco-efficiency as one of several consequences of CE, along with economic value and job creation, reduction in emissions and waste, improved resource security and decreased price volatility for resources (EMF, 2012; EC, 2015a,b; Government of People's Republic of China, 2008). Eco-efficiency can be achieved also in a linear economy by increased resource productivity and waste minimization, as has also been discussed by EMF (2012). In fact, two different concepts has been distinguished by the EMF, the eco-efficiency and eco-effectiveness (EMF, 2012). Eco-efficiency has been defined as an approach of minimization and dematerialization, that is based on the "minimizing the volume, velocity, and toxicity of the material flow system". Eco-effectiveness, on the other hand, entails "the transformation of products and their associated material flows such that they form a supportive relationship with ecological systems and future economic growth. The goal is not to minimize the cradle-to-grave flow of materials, but to generate cyclical, cradle-to-cradle 'metabolisms' that enable materials to maintain their status as resources" (EMF, 2012). It has been suggested that CE should necessarily aim for eco-effectiveness rather than eco-efficiency (EMF, 2012).

Waste prevention is also often present in the reviewed CE approaches, in some of them as the main purpose of CE (WRAP, 2016, Government of People's Republic of China 2008). Waste prevention idea, which may stem from the recognition of the Earth's limited capacity for assimilation of pollution, is common to such concepts as "matter out of place"(Douglas and Isherwood, 1979), "cradle-to-cradle" (Braungart et al., 2007) and "planetary boundaries" (Rockstrom et al., 2009).

Another feature shared by the CE approaches is the mechanism for achieving stock optimization and waste prevention through the main environmental strategies (the Rs): Reduce, Reuse, Recycle and Recover: ". reuse and re-marketing for goods, … and a recycling loop for secondary resources (Stahel, 2013); ' . [CE is] a general term for reducing, reusing and recycling activities (Government of People's Republic of China, 2008); ". recover and regenerate products and materials' (WRAP, 2016); '. system based on the reusability of products and raw materials' (Bastein et al., 2013); ". rather than discarding products …, we should use and re-use them" (Wijkman and Skånberg, 2015). It should be noted, that more nuanced R-typologies exist in the literature, including "Refuse, Repair, Refurbish, Remanufacture and Repurpose" (van Buren et al., 2016).

The intended extent of circularity (either back to the original manufacture or downshifting) differs among the approaches. Only WEF (2016) suggests the complete cycle for CE extent. Repurposing of resources and downshifting is accepted by the approaches presented by EMF (EMF, 2012, 2013, 2015a,b), EC (EC, 2015a,b), and Government of China (2008). Other approaches (WRAP, 2016; Stahel, 2013; Bastein et al., 2013; Wjikman and Skånberg, 2015) advocate for "tight cycles". As has been pointed out by Stahel (2013), the smaller the loop (activity-wise and geographically) the more profitable and resource efficient it is. The "tight cycles" can be expressed as the tightness of the loop within a value chain (Fig. 1). The fewer nodes of the chain have to be passed for the CE activity, the tighter is the loop and the bigger is the preserved value. For example, the loop within Consumption and Use (node 5 on Fig. 1) is more efficient than from Consumption and Use to Re-manufacture, that also involves nodes 6, 7, 3 and 4.

Another difference between the approaches is the suggested scope of CE in terms of the included resources: all physical resources or only certain sectors, products, materials and substances. Approaches presented by the EMF and Government of China are the most comprehensive, advocating for circularity at the levels from materials through products to systems. Several approaches select so-called "priority" materials and/or products, as suggested, for example, by the EC (2015a,b); WEF (2014–2016); WRAP (2016) and Bastein et al., 2013; Stahel (2013) suggests focusing on non-renewable materials while Wjikman and Skånberg (2015) on materials and products in general.

3.2. CE strategies database and CE implementation database

The constructed CE Strategies Database (Table 2) summarizes the methods of CE implementation described in the literature. All the approaches described in the reviewed CE literature and that conformed to the "strategy" definition given in the Method section, have been included as the CE strategies. Because CE is a result of convolution of several sustainability concepts, also the strategies used are often borrowed from other sustainability fields. The Database is envisaged as a basis for designing CE implementation by actors on a system scale (NGOs, sector associations and policy makers) and by the actors managing a value chain or a part of a value chain (Fig. 1). For an illustration of the strategy implementation, over 100 implementation cases for 35 of the total 45 strategies described in the CE Strategies Database can be found in the CE Implementation Database (Supplementary Table). In this database, strategies are arranged and numbered in the alphabetic order and the value chain part number is given. The CE Strategies Database applies the same two indexes, in particular the first one is the part of the value chain that is addressed and second is the strategy sequence number when the strategies are ordered alphabetically. This allows cross-referencing between the two databases. For example, either an index or a strategy name from the CE Strategies Database can be looked up for examples in the CE Implementation Database.

A new classification has been developed for the CE Implementation Database in order to enable search of examples of suitable strategies for CE implementation, among other possible database use scenarios as described below. The classification regards i) Scope of the CE, defined as a Substance, Material, Product, Sector or System and ii) the Strategy name, number and Part of the Value Chain, and iii)Implementation Level of the strategy, defined as Policy/Planning/Vision, Research & Development, Knowledge and Experience Transfer, Pilot Scale, and Market Ready (Table 3 and Supplementary Table). Sectors and systems can either be incomplete value chains or a combination of several value chains. The classification within the category Scope reflects different subjects for CE implementation as suggested in the theoretical approaches and policy documents (see 3.1.1 CE Concept Overview). Some of these theoretical approaches suggest focusing on systems or sectors, while other on priority products, materials or substances. The Strategy name, number and Part of the Value Chain provide ability to look up the strategy definition in the CE Strategies Database and the focus of this strategy within the CE Value Chain scheme (see Fig. 1). On the other hand, the lack of strategies or tested cases for a certain Scope or Part of the Value Chain can be identified (see discussion on CE Implementation Scene in Section 3.3 and Fig. 2). The Implementation Level allows analyzing the available experience for different Scopes and the maturity of the available strategies. The CE Implementation Database can also be used for information on strategies available for a certain Scope in question (i.e. Metal) and for looking up which strategies are application-ready (Pilot Scale and/or Market Ready).

It can be noted that the CE Implementation Database contains a mixture of cases from various actors, including academia, NGOs, consultancy and companies. These actors may have different agendas and standards. From one side, classifying the cases depending on the actor was considered unsuitable because there is a considerable overlap between studies by the academia, NGOs, consultancy and companies. On the other hand, it is a strength of the CE Implementation database to contain cases from different types of actors, as this content is also useful to different actors. In addition, a diversity of actors is necessary to exemplify different levels of CE strategies maturity – from a vision (e.g. governments, NGOs), to research and development (e.g. academia, companies), to market implementation (often by companies). Therefore, when using the CE Strategies Database and the CE Implementation database as a search engine for finding appropriate strategies, it is recommended to pay attention to the agenda and standards of the entity which has developed each of the found cases.

The developed databases can serve as tools for implementation of the suggested in the literature theoretical approaches. In particular, CE Strategies Database and CE Implementation Database include strategies and implementation examples, respectively, for each part of the value chain. The CE Implementation Database contains case studies and the corresponding strategies for various Scopes of CE from substance to sector and system. For example, search for strategies suitable for the ReSOLVE framework business actions (EMF, 2015a) would result in the following selection: Regenerate (strategies #1, #33), Share (#22, #31, #34, #37 and #44), Optimise (#8, #27, #30), Loop (#6, #17, #18, #20, #31, #40, #44), Virtualise (#45), and Exchange (#6, #7).

Table 2
Circular Economy Strategies Database.

	1- MATERIALS SOURCING	
8	Diversity and cross-sector linkages	Establishment of industry standards to promote cross-sector collaboration through transparency, financial and risk-management tools, regulation and infrastructure development and education.
14	Energy production/Energy autonomy	Energy production from by-products and/or residual/process/waste heat recovery to support facility operation.
19	Green procurement	A process whereby public authorities/companies choose to procure goods and services with the same primary function but lower environmental impact as measured, for example, by LCA-based comparison of goods and services.
23	Life Cycle Assessment (LCA)	LCA is a structured, comprehensive and internationally standardized method. It quantifies all relevant emissions and resources consumed and the related environmental and health impacts and resource depletion issues that are associated with any goods or services (EC, 2010).
25	Material substitution	Replacing materials for the more abundant/renewable, hence making the production process more resilient to price fluctuations and resource scarcity.
41	Taxation	Taxes on technologies, products and inputs that are associated with negative externalities.
42	Tax credits and subsidies	Reducing the tax on resources, for example on bio-based materials and products.
	2- DESIGN	
5	Customization/made to order	Products are tailor-made to meet the needs and preferences of the customer. Can reduce waste and prevent over-production. Customers who are satisfied with the products will return to the manufacturer to extend the service life of the products and keep their preferred features. Customer loyalty to the manufacturer is built in.
6	Design for disassembly/recycling	Design that considers the need to disassemble products for repair, refurbishment or recycling.
7	Design for modularity	Products composed of functional modules so that the products can be upgraded with newer features and/or functionalities. The modules can be individually repaired or replaced, thereby increasing longevity of the product core.
10	Eco design	Product design with a focus on its environmental impacts during the whole lifecycle.
30	Reduction	Design and manufacturing involving reduction in use of materials and elimination of harmful substances use.
	3- MANUFACTURING	
13	Energy efficiency	Providing the required services with reduced energy input, which can be achieved by reduced consumption and energy efficient processes.
26	Material productivity	At the company level: the amount of economic value generated by a unit of material input or material consumption. On the economy-wide level: GDP per material input/consumption.
32	Reproducible & adaptable manufacturing	A transparent and scalable production technology that can be emulated at other places using indigenously available resources and skills.
	4- DISTRIBUTION AND SALES	
27	Optimized packaging design	Efficient packaging design strategies abiding regulations and utilizing end-of-life of packaging material.
35	Redistribute and Resell	Resale extends the product life by second hand use. Therefore, fewer products, which serve for the same purpose, have to be produced. The complete products or their components can be re-sold.
	5- CONSUMPTION AND USE	
4	Community involvement	The voluntary involvement of community and different stakeholders in organizing sharing platforms and providing guidance on product repair and replacement.
11	Eco-labelling	A voluntary environmental protection certification of proven environmental preference of a product/service within its respective category. Credible and impartial labelling of product/service is usually overseen by public or private third parties.
28	Product as a service or Product Service System	The ownership of the product rests with the producer who provides design, usage, maintenance, repair and recycling throughout the lifetime of the product. The customer pays a rent for the time of its usage.
29	Product labelling	Aimed to guarantee that consumers have full information on the constituents, origin of raw materials etc. to enable them to make informed decisions. Indicates no environmental or otherwise preference for certain products, in contrast to #11 Eco-labelling.
34	Re-use	Direct secondary re-usage extends the product life by second hand use. Therefore, fewer products, which serve for the same purpose, have to be produced. The complete products or their components can be re-used.
37	Sharing	Shared use/access/ownership of for example space and products and sharing platforms enabling shared use. Multi-purpose space.
38	Socially responsible consumption	A socially responsible consumer purchases products and services that are perceived to have less negative influence on the environment and/or that support businesses that also have positive social impact.
39	Stewardship	Taking responsibility in protecting the resource through conservation, recycling, regeneration, and restoration. A common good is considered, for example a natural resource, in contrast to #16 Extended Producer Responsibility
45	Virtualize	Dematerialization. For example electronic books/CDs, online shopping, use of telecommunication to decrease use of office space and travel.
	6- COLLECTION AND DISPOSAL	
16	Extended Producer Responsibility (E.P.R)	"Extended Producer Responsibility is as an environmental policy approach in which a producer's responsibility for a product is extended to the post-consumer stage of a product's life cycle" (OECD, 2015).
21	Incentivized recycling	A method for rewarding consistent and repeated recycling of recyclable materials, for example a deposit refund
24	Logistics/Infrastructure building	Facilities to promote cost-effective, time-saving and environmentally safe post-consumer collection and disposal. Solutions that render optimum collection.
36	Separation	The biological constituents should be separated from the technical or man-made/inorganic constituents. The technical nutrients ought to be used for remanufacture and the biological nutrients are to be restored or degraded naturally.
40	Take-back and trade-in systems	Efficient take-back systems ensure that the products are recovered from the consumer after end of life and proceed to be remanufactured. Take-back systems could ensure a continuous flow of material for remanufacture.
	7- RECYCLING AND RECOVERY	
2	By-products use	Byproducts from other manufacturing processes and their corresponding value chains are used as raw materials for manufacturing new products.
3	Cascading	Materials and components used across different value streams after end of life. The embedded extraction, labor and capital are conserved across the cascade.
9	Downcycling	It is the process of converting used products into different new products of lower quality or reduced functionality.
12	Element/substance recovery	The process of recovering metals, non-metals and other re-usable substances from a material waste stream.
15	Energy recovery	The conversion of waste materials into useable heat, electricity, or fuel through a variety of waste-to-energy processes, including combustion, gasification, pyrolysis, anaerobic digestion, and landfill gas recovery.

(*continued on next page*)

Table 2 (*continued*)

		1- MATERIALS SOURCING
17	Extraction of bio-chemicals	Conversion of biomass into low-volume but high-value chemical products, thereby generating heat, power, fuel or chemicals from biomass.
18	Functional recycling	Process of recovering materials for the original purpose or for other purposes, excluding energy recovery.
20	High quality recycling	The recovery of materials in pure-form without contamination, to serve as secondary raw materials for subsequent production of the same or similar quality products.
22	Industrial symbiosis	Exchange and/or sharing of resources, services and by-products between companies.
33	Restoration	Also known as composting. Process where biological nutrients are returned to the soil after break-down by micro-organisms and other species.
43	Upcycling	Converting materials into new materials of higher quality and increased functionality.
		8- REMANUFACTURE
31	Refurbishment/Remanufacture	Rebuilding a product by replacing defective components by reusable ones.
44	Upgrading, Maintenance and Repair	The most efficient way to retain or restore equipment to desired level of performance is maintenance. Moreover, service after-sales is considered key for competitive advantage and business opportunity. Maintenance is also carried out in the form of repair. To eradicate product obsolescence or extend the useful life of the product, services like upgrading are necessary.
		9-CIRCULAR INPUTS
1	Bio-based materials	Resource inputs or materials that last for longer than a single life-cycle and can easily be regenerated.

3.3. State of the art in circular economy implementation

Currently, two main directions in CE implementation can be distinguished in the literature on CE theory and policy: i) a systemic economy-wide implementation, e.g. at the local, regional, national and transnational level and ii) implementation with a focus on a group of sectors, products, materials and substances.

A systemic economy-wide implementation on three levels has been envisioned in China: the macro-scale (city, province and state), the meso (symbiosis association) and the micro (objects) scales (Su et al., 2013). In the Netherlands, CE has been proposed to be implemented on the economy-wide scale with an ambition to make the Netherlands a "circular hotspot". In particular, the Dutch government launched the Green Deal initiative in 2013, followed by the Realization of Acceleration of a Circular Economy (RACE) project in 2014. In RACE, the work-packages range from design and knowledge-sharing to demonstration projects and community involvement. Another systemic CE implementation considers the production sector, where transnational policies adopting CE principles have been launched under the UNIDO/UNEP Programs for Sustainable Consumption and Production, National Cleaner Production Centres, and the UNEP's Life Cycle Initiative. At the regional and local levels, the most common example of systemic CE implementation are the industrial parks, in particular so-called eco-industrial parks. These are based on the idea of industrial symbiosis – sharing of resources and recycling of waste across industries. The Kalundborg Park in Denmark is a classic example, with over 40 years in operation (Ehrenfeld and Gertler, 1997), and many more industrial parks exist in China (Shi et al., 2010).

Another CE implementation approach is based on focusing on a group of sectors, products, materials or substances. The European Commission's proposed Action Plan to promote a circular economy (EC, 2015a,b) includes legislative proposals for waste management sector regarding reduction of landfilling, increased preparation for reuse and recycling of key waste streams such as municipal waste and packaging waste, as well as improvement of extended producer responsibility schemes. Other legislative proposals include promotion of economic incentives, comprehensive commitments on eco design (which currently concerns only energy-consuming devices), and targeted action in areas such as plastics, food waste, construction, critical raw materials, industrial and mining waste, consumption and public procurement. Additional legislative proposals on fertilizers and water reuse were announced to be released in the future. Among the prioritized for CE implementation products are electric and electronic equipment and textiles (EC, 2015a,b; WRAP, 2016), furniture, packaging and tires (EC, 2015a,b). The prioritized secondary raw materials list includes plastic, metals, paper and cardboard, glass and biodegradable waste (EC, 2014a,b; World Economic Forum, 2014a). The WEF argues that materials represent the "greatest common denominator" across industries and geographies. Therefore, the WEF advocates implementation of a CE by using pure, high-quality materials with cross-industry applications. The purity of materials is envisioned to be standardized, which will allow to aggregate volume of same quality secondary materials and develop reverse loops of material supply at a global level.

When the practice of CE implementation is considered, the collected CE Implementation Database allows construction of a snapshot of state of the art of CE implementation, which we call here the Circular Economy Implementation Scene (Fig. 2). It should be noted, that this scene is not comprehensive as it is bounded by the time of the literature search (spring 2015) and the keyword "circular economy". Yet, we believe that large number of cases and their diversity provide a reasonable depiction of the implementation state of the art. On Fig. 2 a frequency analysis of the implementation cases in each of the classification categories is presented. The X-access shows number of cases. Width of the cells in the horizontal bars is proportional to the number of cases using the same strategy (strategies are identified by the number on the cells).

As can be seen from Fig. 2, the part of the value chain that has received the most attention is the Recovery and Remanufacture. Combined with the implementation cases for Collection & Disposal part of the value chain, these two categories comprise almost half of all the implementation cases. This situation may be a result of the historical development of CE implementation elements from the waste management sector. For illustration, an example of waste management development in Europe can be used. A waste hierarchy was formulated and proposed to Dutch Parliament in 1979 Ad Lansink (Parto et al., 2007) and has been adopted in the "A Community Strategy for Waste Management" (EC, 1989). Subsequently, a strict waste hierarchy was introduced in EU legislation with the 2008 Waste Framework Directive, which distinguishes prevention, preparing for reuse, recycling, recovery, and landfill (EC 2008). In Germany, Waste Avoidance and Management Act, adopted in 1986 prioritized the avoidance and recycling of waste, which provided the foundations of producer responsibility (Szelinski, 1988). Extended Producer Responsibility (EPR) for selected products, such as electronics, batteries and packaging, has also been implemented throughout the EU (EC, 2014a,b). In such a way, waste avoidance principles and tools were formulated and subsequently included as the elements to CE concept. Currently, Japan is leading in the international development when it comes to sustainable resource management by considering in the nationwide policies even so called hidden flows (i.e. extractions that are not used further, but that have an environmental impact e.g. overburden and extraction waste), and, in such away, acknowledging the global impact of Japan's consumption

Table 3
Excerpt of the CE Implementation Database (for complete database see Supplementary Table).

Value Chain Part	Strategy Number	Strategy Name	Scope					Implementation Levels				
			Substances	Materials	Products	Sectors	Systems	Plan, Policy & Vision	Research & Development	Knowledge Sharing	Pilot scale	Market Ready
2	30	**Reduction**		PET Plastic in packaging (reducing wall thickness & weight of caps) [a].			Amount of waste from production and use[b].	Amount of waste from production and use[b].				Nestle Water reduced PET packaging by 19% from 2005- 2010[a].
2	30	**Reduction**		PVC in packaging by 99%[c].								Unilever reduces PVC in packaging by 99%[c].

[d] Allwood et al. (2011).
[a] EMF (2014).
[b] Waste Law of Germany, Swiss Academy of Engineering Sciences (2014).
[c] Unilever (2016).

(because extraction may have occurred outside of Japan). The hidden flows are monitored by the Total Material Requirement (TMR) indicator, which includes both materials that are used for further processing and hidden flows (EEA, 2016).

Another important category for CE implementation was found to be the Consumption and Use part of the value chain. However, despite of a long history of CE practice in the consumer sector by sharing, re-using and repairing of products, the institutional support is at a very early stage. For example, only a recent investigation on the future of waste management, carried out on behalf of the Swedish government, put forward a proposal regarding establishment and institutionalization of centers for sharing, re-use and repair of products (Government of Sweden, 2012).

The common CE principles identified in the theoretical CE approaches are in general well reflected in the CE Implementation Scene. Majority of the principles rely on actions within all parts of the value chain. In particular, the entire CE value chain serves the optimization of stock. Eco-efficiency, defined as minimization of the throughput of the resources, is also supported by strategies in all parts of the value chain, and so is the 4Rs principle. At the same time, the Eco-effectiveness is not enabled by the current CE Implementation Scene. In order to transform the products and their associated material flows, development of the Circular Inputs of the materials is necessary. This was, however, the least represented part of the value chain. To promote Eco-effectiveness, actions within Material Sourcing and Design are also important, however, the examples of the actions are currently underrepresented. The other underrepresented parts of the value chain are Manufacturing, Distribution and Sales.

Monitoring of the progress and the outcomes has to be an integral part of implementation. At this time, monitoring of the CE implementation is under-developed. As has been discussed in the Section 3.1.1. CE Concept Overview, the CE aspirations are mainly grounded in management of the physical resources according to identified principles of stock optimization, eco-efficiency, waste prevention and 4Rs. Therefore, monitoring of the physical flows during the CE implementation efforts should undoubtedly be a basis for the monitoring scheme. Three main approaches addressing monitoring of the physical flows are currently being developed, based on: material flow analysis (MFA), emergy analysis and Input-Output analysis. Of the three approaches, the Environmentally Extended Input-Output method is the most comprehensive because it provides a link to the economic dimension of the CE as well as allows quantifying environmental impacts across the value chains (Genovese et al., 2017). However, the economic data (national input-output tables) used for this method is aggregated to just a few economic sectors, which limits its use for CE monitoring. Emergy-based indicators are not yet properly organized and there isn't a unified theory (Geng et al., 2013), and it should be complemented with environmental impact and economic assessment for a complete evaluation of the CE measures. The same additional assessments are also needed to complement the MFA method. One MFA-based method that incorporates environmental impact assessment is the recently published Hybrid MFA-LCA method (Goldstein et al., 2013; Lavers et al., 2017a,b). This method allows addressing "More comprehensive and integrated representation of flow and stock externalities", which is one of the tasks described in the ReSolve framework report (EMF, 2015b). On the other hand, the economic assessment of the CE measures can be conducted using the MFA results for physical flows of different economy sectors, as has been described elsewhere (EMF, 2015b).

In general, the MFA method is the most mature among the three approaches being developed to date. For instance, MFA is the only method capable of addressing one of the tasks in the ReSolve framework report: "Comprehensive representation of materials and products flows" (EMF, 2015a). In particular, the MFA-based models that have the highest resolution, such as the economy-wide EU model and the UMAn urban MFA model, allow material flows monitoring on material, product, sector, or other system level (Rosado et al., 2014; Kalmykova et al., 2015a,b; Kalmykova et al., 2016). Such monitoring enables studies of the demand composition, projection and management of secondary resources (Kalmykova et al., 2015a,b; Kalmykova and Rosado, 2015; Patricio et al., 2015). Moreover, the models allow the identification of actors managing the flows and may therefore help in policy development and focused engagement of key actors. Another benefit of MFA is availability of time series of MFA results for the past two decades, both on global and national scale, which can be used in analysis and monitoring resource consumption.

The MFA-based indicators for CE implementation have already been established in Japan, which include such indicators as Resource Productivity, Cyclical Use Rate and Final Disposal Amount (Yoshida 2008). In Europe, the European Commission have stated that a monitoring framework for the CE will be developed in 2017, on a basis of the recently launched by the Eurostat Resource Efficiency Scoreboard and the Raw Materials Scoreboard (EC, 2015a,b). Even in this case of monitoring framework, several indicators depend on MFA, such as "resource productivity"(GDP over the Domestic Material Consumption) and Dashboard Indicator on materials (DMC per capita).

4. Conclusions

Currently there are many initiatives underway to implement circular economy (CE). The main actors driving this development are the legislative and governmental bodies, NGOs and consultancy firms. At the same time, no common ground for the variety of existing approaches has been established. This paper contributes to streamlining the CE concept by analyzing the literature on the theory and implementation of the CE, and provides guidance (Table 1) for further reading on different aspects of circular economy.

The existing CE approaches have been analyzed by identifying the common main ideas, such as stock optimization, eco-efficiency and eco-effectiveness, waste reduction and the 4Rs being the main strategies to achieve the CE. On the other hand, differences between the approaches have been identified pertaining to such dimensions of the CE as cycling extent (tightness of the loop within a value chain) and the scope (from a substance to an economic sector).

In addition, two tools has been developed and presented in order to facilitate circular economy design. The CE Strategies Database has been constructed, featuring 45 strategies that are suitable for application in different parts of the value chain. The CE Implementation Database, containing over 100 implementation cases for 35 of these strategies, classifies cases by i) Scope of the CE, defined as a Substance, Material, Product, Sector or System, ii) the Strategy name, number and Part of the Value Chain, and iii) Implementation Level of the strategy, defined as Policy/Planning/Vision, Research & Development, Knowledge and Experience Transfer, Pilot Scale, and Market Ready. This classification enables search of examples of suitable strategies for CE implementation by the part of the value chain, by scope in interest and is useful for looking up which strategies are application-ready (Pilot Scale and/or Market Ready).

The current CE Implementation Scene, regarding the Scope, targeted Parts of the Value Chain and used Strategies has been analyzed. Recovery, Consumption and Use parts of the value chain has received the most attention. Many parts of the value chain such as Manufacturing, Distribution and Sales are rarely involved in CE. Policy measures prevail in the current development, while many early adopters and market-ready solutions exist already. Products, Materials and Sectors are well represented as Scopes for CE implementation while System Scope is rarely addressed. CE Implementation monitoring has also been discussed in this paper. Further development of the monitoring methods based on Material Flow Accounting (MFA) is suggested. Accounting the material flows allows monitoring of changes over time as a way to analyze the efficiency of the CE programs. Recently developed Hybrid MFA-LCA method allows monitoring environmental impact indicators along with the resource use indicators. This is necessary in order to ensure that eco-effectiveness is achieved and to identify unintended consequences of the CE implementation.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.resconrec.2017.10.034.

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