Resources, Conservation & Recycling 163 (2020) 105073

Contents lists available at ScienceDirect

Resources, Conservation & Recycling

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

Review

The narrative of sustainability and circular economy - A longitudinal review of two decades of research

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ARTICLE INFO

Keywords:
Circular economy
Sustainable development
Thematic mapping
Multiple correspondence analysis
Topic modeling
Historiographic analysis

ABSTRACT

Circular economy (CE) has gained momentum in the political, economic and scientific fields. The growing popularity of the concept is accompanied by some definitional ambiguities and conceptual uncertainties. In particular, the relationship and contribution of CE to sustainable development (SD) and thus to a more sustainable society is currently under discussion. The purpose of this paper is to contribute to this discussion by providing new insights into the evolution and state of CE research over the past two decades, in general, and its sustainability connotation, in particular. For doing so, a mixed-methods approach was adopted that combines a longitudinal bibliographic network analysis, multiple correspondence analysis and k-means clustering, correlated topic modeling, historiographic citation analysis and a semantic content analysis. The results indicate that the CE literature body can be divided into management and technically-oriented studies that have either a beginning-of-life or an end-of-life focus. Recycling is the most referred to R-strategy, followed by remanufacturing, repair and reuse, which, however, occur one order of magnitude less frequently. CE research and SD were found to exhibit a subset relationship, as only a limited number of environmental aspects is directly addressed. Social aspects form a periphery. The qualitative analysis further portraits the conceptual evolution of the CE-SD relationship between 2000 and 2019 by following the citation network of the 30 most influential CE papers. The results contribute to positioning CE research within the general Sustainable Development debate and to identifying potential, sustainability-related shortcomings and blind spots.

1. Introduction

With the introduction of circular economy (CE) policies in major regions of the world economy (namely, in China in 2002, and in the EU in 2015) interest in the concept has increased significantly in the past few years (European Commission, 2015; Yuan et al., 2006). For the EU, it presents the possibility of promoting environmental benefits, sustained economic growth, and added value, all in addition to job creation, and hence acts to support all three sustainability pillars at once. At the same time, the transition towards a more circular economy is supposed to contribute to several sustainable development goals (SDGs), most prominently to SDG 12, sustainable production and consumption patterns (European Commission, 2015), but also to SDG 6, SDG 7, SDG 8, and SDG 13, on water, energy, economic growth, and climate change, respectively (Geng et al., 2019; Schroeder et al., 2018).

The popularity of the CE concept in politics is also mirrored in a growing interest in scientific research (Reike et al., 2018). The approach in the scientific sphere, however, entails much more ambiguity, and the narrative employed is less clear cut (Korhonen et al., 2018a). For example, the potential global impact of CE, its framing and definition, and hence the scope of the concept, are currently under discussion (Kirchherr et al., 2017). This has resulted in a highly dynamic, somewhat erratic field of research (Homrich et al., 2018; Merli et al., 2018). There is thus a growing need for clear conceptualization and the establishment of a common understanding and approach to CE, in order to define limits and interfaces in respect to other concepts and models. Efforts have recently been undertaken by several scholars, for example, to frame (aspects of) CE (Urbinati et al., 2017a; Zotti and Bigano, 2019), revise the measurement and assessment of CE (Parchomenko et al., 2019; Pauliuk, 2018), to understand the definitional ambiguities of CE (Kirchherr et al., 2017), or to establish relations to sustainable development in general, as well as to define how it is related to specific concepts such as industrial ecology (IE), green/bio economy or eco-design (D'Amato et al., 2017; Millar et al., 2019; Saavedra et al., 2018).

However, due to the concept's inherent versatility and ambiguity, a

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https://doi.org/10.1016/j.resconrec.2020.105073
Received 14 April 2020; Received in revised form 4 July 2020; Accepted 25 July 2020
0921-3449/

substantial need for more definite conceptualization still remains (Reike et al., 2018). Specifically, the relation and contribution of CE to sustainable development (SD) and, therefore, to a more sustainable society, is currently under discussion, including the possible positive and negative effects of a more circular economy with respect to SD. Geissdoerfer et al. (2017) summarize - based on an extensive, qualitative literature review - how scholars perceive the relationship between the two concepts. They find eight different relationship types that fall into the following three groups: the relationship between CE and SD can be either conditional (CE is a condition for SD), beneficial (CE benefits SD), or it may take the form of a trade-off (CE comes with costs and benefits regarding SD). Furthermore, Millar et al. (2019), via a qualitative literature review, also explore the extent to which CE can serve as a tool for SD. They find that it is still unclear how CE shall promote economic growth while both protecting the environment and ensuring intra- and inter-generational social equity, and suggest that the inclusion of social aspects and behavioural economics would be necessary in order to achieve the goal of supporting SD. Apart from these studies on the integration of CE and SD, no study so far has addressed the relation between CE and SD on both a quantitative and a qualitative basis. The present study, therefore, is an attempt to close this gap in the research by placing the CE literature within a broader scientific context, and by analyzing, first in general, the state and evolution of CE research, and then more specifically, the relation between CE and SD. Three research questions guided the research process:

- **RQ1:** What research streams, concepts and topics can be distinguished in the field of circular economy, from a longitudinal perspective?
- **RQ2:** What is the role of sustainable development in the circular economy research debate?
- **RQ3**: Which papers define the debate on a circular economy and on sustainable development? How do they describe the relationship semantically?

To answer these research questions, the paper is structured as follows: Section 2 briefly summarizes previous bibliometric studies related to CE and clarifies the focus of the paper at hand. Section 3 covers a description of the mixed methods applied in this study, including (longitudinal) bibliographic network analysis, multiple correspondence analysis, k-means clustering, correlated topic modeling and historiographic citation analysis, on the quantitative side, and semantic content analysis, on the qualitative side. The results of the investigation are then presented in Section 4, first, by showing and analyzing the evolution of themes and clusters in CE research, together with their interrelation with SD and, second, by analyzing the correlations between sustainability and CE, based on a qualitative analysis of relevant papers. The findings are then discussed in Section 5, and conclusions, final remarks and limitations are dealt with in Section 6.

2. Overview and delimitation with respect to previous reviews of CE literature

Several scholars have analyzed the rapidly evolving field of research on the circular economy using bibliometric methods. However, these studies exhibit varying focuses, and up to now, no study has investigated the relationship between CE and SD quantitatively. Only Homrich et al. (2018), who conducted a general bibliometric analysis of CE research, also dedicated a section to the CE-SD relationship. However, they only focused on 39 CE and supply chain-related publications, and then assigned these to the three dimensions of sustainability. Further bibliometric studies either focus on CE in general (Ruiz-Real et al., 2018; D'Amato et al., 2017), CE in a Chinese context (Cui and Zhang, 2018; Türkeli et al., 2018), or have a narrow focus on the internet of things (IoT) and big data (Nobre and Tavares, 2017).

Among these studies, Ruiz-Real et al. (2018) highlighted three main trends in CE research, namely eco-innovation, eco-design, and waste management, and mentioned assessment-related topics, as well as sustainable development, as an upcoming connection to CE. D'Amato et al. (2017) compared the literature on the circular, green and bioeconomy, as all three of these concepts imply a change in the current economic system towards a more sustainable one. According to the authors, the three concepts mainly evolved around relative decoupling within economic growth. Additionally, the idea of a green economy also merges into green growth, and the literature on the bioeconomy is mixed in with concepts covering green growth and business as usual scenarios. Cui and Zhang (2018) compared the scientific literature on a circular economy and related the topics to Chinese public policy, and found clear interactive feedback. They call for a more spatial approach towards CE, including urban and regional metabolisms. Türkeli et al. (2018) analyzed CE development in China and in the European Union and the potential for research cooperation between these two leading regions. They confirm that there is a high potential for international cooperation within the automotive, construction, and demolition sectors, as well as in developing suitable business models and resource security. Finally, Nobre and Tavares (2017) find that although the IoT and big data applications can be seen as crucial enablers for CE approaches, their inclusion in the literature remains relatively scarce (70 publications), thus indicating a gap in the research.

The study at hand distinguishes itself from this previous bibliometric work on the CE in terms of both its scope and the methods used. The scope is aimed explicitly at the intersection of CE and SD and covers the full period of research, including the years 2017, 2018 and 2019, in which 88% of all CE-related papers (based on our sample of 3822 papers) were published. Only Ruiz-Real et al. (2018) included 2017 (but focused on a CE + environment subset). No study so far has included 2018 or 2019. The mixed methods approach applied here provides a systematic quantitative and qualitative insight into the role of SD in CE research, from a longitudinal perspective. The majority of the quantitative methods, have, to the best of the authors' knowledge, not been adopted in previous CE-related studies. A further point of distinction with respect to previous studies lies in the cleaning of the datasets used in the analysis. This was done in order to obtain the best possible data quality and to ensure appropriate matching during the computational analyses. Duplicate papers were removed, keywords were cleaned (e.g., by merging synonyms or removing method-related keywords), and the cited references, author, as well as paper-related metadata, were homogenized throughout the dataset.

In summary, this study sets out to (1) expand upon previous, qualitative research on the CE-SD relationship and to (2) provide new insights into the evolution and state of CE research in general, through the use of several new methodological lenses. In light of the exponential growth in circular economy-focused research, the insights gained from these analyses can be vital in positioning CE research within the overall sustainable development debate and in identifying potential sustainability-related shortcomings and blind spots in the emerging CE literature - ultimately to guide future research. In the following, the research process and the methods are described.

3. Methods

This paper follows a mixed-methods approach to analyze the body of literature at the intersection of circular economy and sustainability research.

3.1. Data sampling, collection and cleaning

The sample of publications for analysis was obtained using two different search strings. The first only used ”circular econom*” while the second used “circular econom*” AND “sustainab*”, in the Scopus and the Web of Science (WoS) databases. Ancillary search terms (e.g., industrial ecology, bio-economy, closed-loop supply chain management, …) were intentionally omitted because the research aim was to accurately map the emergence of the specific concept "circular economy" and its relations to sustainable development. Furthermore, this unambiguous and focused search strategy ensured the comparability of the datasets (D'Amato et al., 2017) ,[1] and the interpretability of the results.

In both databases, the search was conducted in February 2020 and limited to journal papers and reviews (i.e., conference proceedings and books were excluded) published up to and including December 2019. No further limitations were made (e.g., regarding the publication language or the first publication date). As illustrated in Fig. 1, after removing duplicates in the two databases, a total of 3822 peer-reviewed papers on the circular economy, with the first in 2000, and 2149 peer-reviewed papers referring to circular economy and sustainability, with the first one in 2004, were used in the analyses. The systematic literature review procedures described by Fink (2005) and Tranfield et al. (2003) served as a general underpinning for the data sampling and collection process.

Before the quantitative and qualitative analyses were conducted, the datasets were cleaned and corrected: As preparation for the keyword-based analyses, synonyms such as Life Cycle Assessment and Life Cycle Analysis were merged and keywords that did not convey a topic-related meaning (e.g., paper, review, study, priority journal, …) were deleted. This cleaning process was undertaken for both types of keywords used in the analyses, i.e. for those keywords assigned to a manuscript by the authors (Author keywords) and for those that are assigned by the publishers and databases (referred to as Keywords Plus). Finally, discrepancies and errors in the reference data were also corrected to obtain a clean dataset for the historic citation analysis.

3.2. Data analysis

As illustrated in Fig. 1, five different research steps were conducted, and the respective results were used to answer the research questions. The full CE dataset ($n = 3822$) provided input for (1) the thematic mapping, (2) a multiple correspondence analysis (MCA) and k-means clustering, and for (3) fitting a correlated topic model. To provide a basis for the qualitative content analysis, the focus was furthermore set on the intersection of CE and SD research ($n = 2194$) and (4) a historical citation network analysis was conducted for this dataset. Finally, the 30 most influential papers identified in step (4) were analyzed by means of a (5) qualitative content analysis according to the step-wise approach suggested by Mayring and Gläser-Zikuda (2008). For the network and statistical analyses, R version 3.5.1 (R Core Team, 2018) was used. The data and the full reproducible code are available at https://osf.io/u2baw/.

The study thereby followed a hybrid of a concurrent mixed design (steps (1) to (3) (=quantitative analysis) and step (5) (=qualitative analysis) are evaluated independently and contrasted with each other) and a sequential mixed design (the quantitative analysis in step (4) informs subsequent qualitative research in step (5)) (Teddlie and Tashakkori, 2006). In the following, each of the specific methods illustrated in Fig. 1 is briefly described, before the results are presented in Section 4.

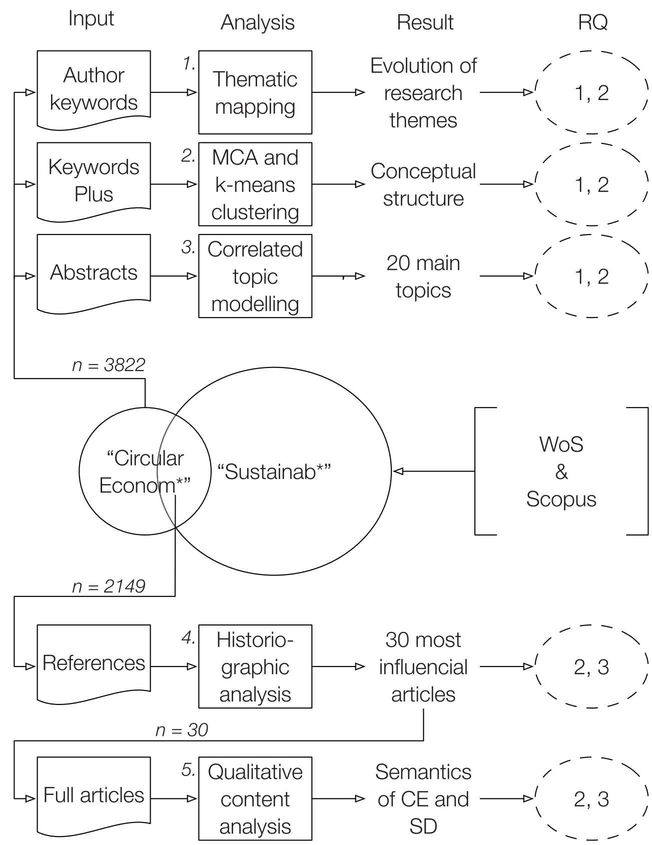

Fig. 1. Outline of the research steps. MCA = Multiple Correspondence Analysis. CE = Circular Economy. SD = Sustainable Development.

3.2.1. Thematic mapping (step 1)

The longitudinal bibliographic network analysis approach by Cobo et al. (2011) was adopted in order to map the thematic evolution of CE research. In contrast to static approaches, which neglect the temporal dynamics of a research field, thematic mapping uncovers these dynamics by allowing the identification of associations of research themes not only within one, but also within and between several time-resolved networks. These networks were created based on the co-occurrence of keywords that are assigned to peer-reviewed papers. Author keywords were used as input for the thematic mapping because these serve as a proxy for the specific content of the paper. The creation of co-occurrence networks is an established technique for scientific knowledge mapping (Radhakrishnan et al., 2017). In such a network, each keyword is represented by a node. An edge between two nodes indicates their co-occurrence in a paper. How often two keywords are used together is illustrated by an edge's weight. By applying network clustering algorithms, such as the Louvain method (Blondel et al., 2008), which was used in the study at hand, meaningful knowledge communities and their associations with each other can be identified and illustrated. In line with the terminology of Cobo et al. (2011), here and in the following, such knowledge communities will be referred to as "themes". For the normalization of the co-occurrence data, the association strength (i.e., proximity index or probabilistic affinity index) was used (Van Eck and Waltman, 2009). The result of the thematic mapping analysis is, thus, a set of themes that is obtained for a specific number of subperiods. Thematic maps were used to visualize the results, alongside the calculation of appropriate network metrics.

Fig. 2a shows a schematic of a network of themes on which the thematic mapping is based.

Fig. 2b shows a schematic of a resulting thematic map that is used to portray the identified themes in a 2-dimensional space, with respect to their density and centrality (Callon et al., 1991).

[1] Authors such as Saavedra et al. (2018) or Nobre and Tavares (2017) used a wider range of search terms related to CE. However, as each keyword that is used in a search string will have, in most cases, also a relatively high frequency of occurrence and a high degree of connections to other keywords in the dataset, the sustainability connotation of circular economy-related research might have been obscured by also considering ancillary terms. The present approach is also considered justified given the exponential increase in the number of publications on the concept of CE and the growing number of studies that define and delimitate the field.

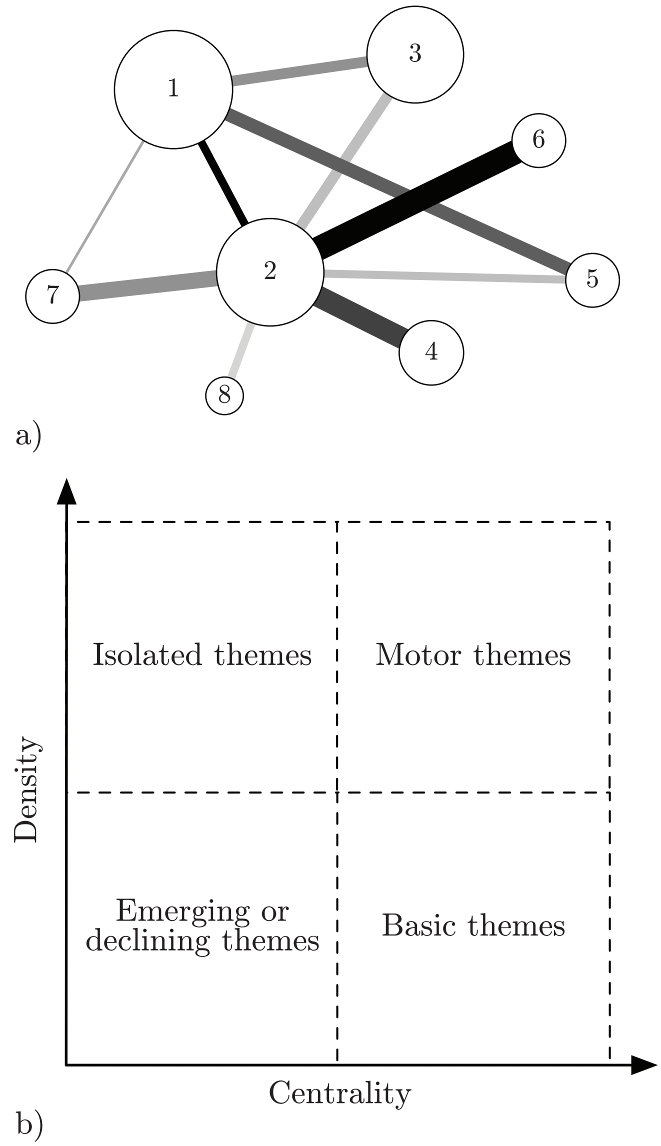

Fig. 2. a) Scheme of a thematic network, b) Scheme of the four quadrants of a thematic map (based on Cobo et al., 2011).

The density measures the strength of a theme's internal ties (i.e., between the keywords belonging to the respective theme) and the centrality, the strength of external ties to other themes. According to these two network parameters, the themes can be categorized into the following four quadrants:

1 Emerging or declining themes (low density/low centrality). Themes in this quadrant have relatively few internal and external ties to other themes. Thus, they can be considered as being of marginal importance in the respective field.
2 Isolated themes (high density/low centrality). These themes can also be considered as peripheral, but in contrast to emerging/declining themes, they have stronger internal ties, i.e. a higher density, and can thus be considered as specialized.
3 Basic or transversal themes (low density/high centrality). They are of high importance to the field, as they have a relatively high number of external ties, i.e. a high centrality.
4 Motor themes (high density/high centrality). As basic themes, motor themes are also important for the structuring of a research field. In addition, however, the keywords in a motor theme also exhibit strong internal ties, i.e. they appear more commonly together, making them relatively more "developed" (Cobo et al., 2011).

3.2.2. Multiple correspondence analysis (MCA) and k-means clustering (step 2)

The general conceptual structure of CE research was investigated by using a tandem approach of correspondence analysis and k-means clustering (Mitsuhiro and Yadohisa, 2015), using the R-package "bibliometrix" (Aria and Cuccurullo, 2017). Multiple correspondence analysis (MCA) is a multivariate statistical method for visualizing contingency tables. The method dates back to Hirschfeld et al. (1935) and found wider application after the advancements made by authors such as Hill, Benzécri and Greenacre (Sourial et al., 2009). It is a dimension reduction technique that can be applied to nominal data and, thus, is closely related to multi-dimensional scaling and factor analysis for ordinal and metric data (Backhaus et al., 2015). As input for the analysis, "Keywords Plus[2]" were used and not the "Author Keywords". These keywords also include less specific descriptors of the papers' contents and, thus, convey broader meanings, making them well suited for analyzing the conceptual structure of a scientific field (Zhang et al., 2016). To identify clusters in the conceptual structure obtained via the MCA, a k-means clustering algorithm was applied to the data. The number of clusters was first automatically determined using the "bibliometrix" package and then refined based on expert evaluation. More details on the method can be found in Greenacre (2007) and Backhaus et al. (2015).

3.2.3. Correlated topic modelling (step 3)

To contrast and expand upon the two keyword-based analyses, the abstracts of the 3822 CE-related papers were subsequently analyzed using correlated topic modeling (CTM). Abstracts serve as an additional data source, since they include more text and convey more differentiation than the keywords. CTM is a topic modeling method that expands upon the latent dirichlet allocation (LDA) developed by Blei et al. (2003). CTM was introduced by Blei and Lafferty (2007), and in CTM, in contrast to LDA, correlations between topics are possible. The CTM in the study at hand was conducted with the R-package "topicmodels" (Grün and Hornik, 2011) and the optimal number of topics was estimated using the R-package "LDAtuning" (Nikita, 2019) (see Fig. C1 in Appendix C). After this optimization-based topic determination, a range of models with the following different variations of k (k = 15, 20, 50) were fitted and evaluated by the authors, in order to select an interpretable solution for inclusion in the paper.

3.2.4. Historiographic analysis (step 4)

A historiographic analysis was conducted in order to identify influential papers in the CE and SD debate. To do so, the R-package "bibliometrix" (Aria and Cuccurullo, 2017) was used. Historiographic analysis is used for creating a chronological citation network in which the most cited papers within a bibliographic collection are depicted. Thus, the local citation score is used for measuring the influence of a paper within a specific research stream. Consequently, it is possible to identify and analyze papers that shape a specific topic. "Bibliometrix" follows the approach suggested by Garfield (2004). The rationale behind this approach is the assumption that researchers publish their findings in peer-reviewed journals, and that they base their own research on similar research which has already been published (Fetscherin and Usunier, 2012; van Raan, 2003). By creating a historic citation network of the 30 most frequently cited papers within the bibliographic collection containing peer-reviewed papers on "circular econom* AND sustainab*" (i.e. the CE and SD literature set, n = 2149),

[2] In Web of Science, Keywords Plus are assigned using an algorithm that "… *provides expanded terms stemming from the record's cited references or bibliography*" (Clarivate Analytics, 2020). In Scopus, Keywords Plus are assigned manually (Elsevier, 2020)

it was possible to identify the central publications shaping the debate around these two topics. The resulting 30 papers were chosen for two reasons: first, a total of 30 papers was seen as providing an acceptable compromise between the desire to include as much input as possible and the need to keep the workload to a realistic level in subsequent qualitative analysis. Second, other analyses have used a similar number of papers for qualitative analysis when complementing quantitative reviews (Apriliyanti and Alon, 2017). Consequently, it is assumed that 30 is an adequate number of papers to include in the historiographic analysis.

3.2.5. Qualitative content analysis (step 5)

Based on the results of the historiographic analysis and the corresponding historic citation network, a qualitative content analysis of the 30 most influential papers from the bibliographic collection on circular economy and sustainability was carried out. By adding a qualitative layer to the analysis, the quantitative findings are expanded and deepened. Furthermore, the qualitative analysis goes beyond the numeric relationships and reaches into semantics (see Elijido-Ten and Clarkson, 2019, for a similar approach). The qualitative content analysis was based on Mayring's (2010) suggestions and entails a process of content structuring. Since the aim was to investigate the relationship between sustainability and circular economy semantically, the material was analyzed with respect to subcategories connecting both of these concepts.

4. Results

4.1. Thematic mapping revealing the temporal dynamics of CE research

As illustrated in Fig. 1, the full circular economy dataset of 3822 publications spanning from 2000 to 2019 was used for the thematic mapping. This dataset was split into four time slices. Due to the low number of circular economy-related peer-reviewed publications in the early years, and the exponential growth in recent years, the data had to be cut into uneven slices. One slice comprises 13 years (2000–2012, n = 230 papers), two slices comprise 3 years each (2013–2015, n = 236; 2016–2018, n = 1794), and one slice comprises one year (2019, n = 1648). Thus, the first two slices and the second two slices contain a comparable number of papers. The split between the first and the second slice furthermore marks the publication of the first major CE-related report by the Ellen McArthur foundation in 2012 (Ellen MacArthur Foundation, 2012). The split between the second and the third slice marks the introduction of the CE package by the EU in 2015 (European Commission, 2015). The year 2019 was included separately, as in this period almost the same number of papers was published as in the previous three years.

For each of the four time slices, the 1000 most frequent author keywords were included in the network analysis. Themes and keywords that occurred at least five times (min Freq.) per subperiod were furthermore also illustrated in the resulting three thematic maps (Fig. 3-6). In each thematic map, the y-axis measures the density, and the x-axis the centrality (Section 3.2.1), of the identified themes in the thematic co-occurrence network. The volume of the spheres is proportional to the cumulative frequency of the keywords (see Tables A1-A4 in Appendix A).

4.1.1. CE research between 2000 and 2012

As can be seen in Fig. 3, during the first thirteen years of CE-related research, a total of four themes could be identified in the keyword co-occurrence network using the Louvain algorithm. The largest theme was the one that formed around circular economy (cumulative Frequency, cF = 119 – illustrated by the size of the spheres in the thematic map). This CE-related theme, with average centrality and density values, was on the verge of being a motor theme. In contrast, the second-largest theme "china & industrial ecology" (cF = 81) represented a basic theme, indicating the central role of industrial ecology (IE) and that of China during early CE research. The third-largest theme coalesced around "sustainable*" (cF = 29) and it also served as the only motor theme during the early years of CE research. However, besides sustainab*, no other, more specific sustainability-related keywords met the minimum frequency criteria. The fourth and final theme during this period was the method-related theme "material flow analysis", which, however, only represented one isolated theme (cF = 9).

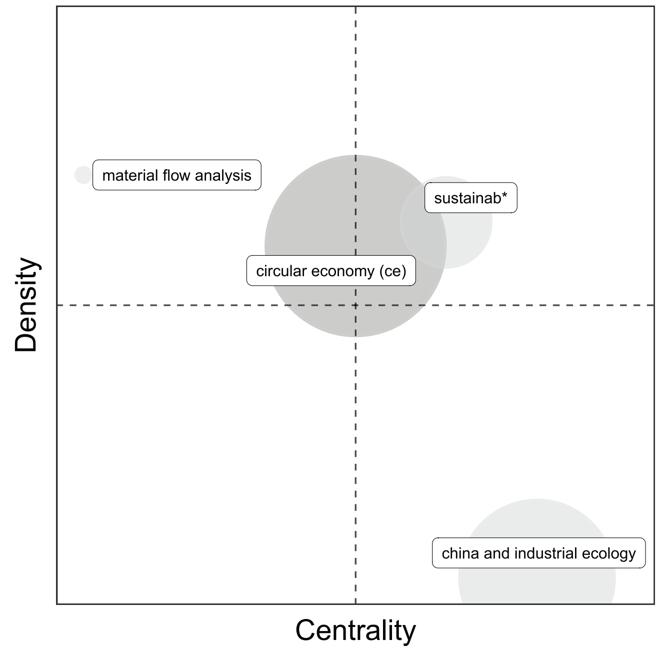

Fig. 3. Thematic map of circular economy research between 2000 and 2012 (n = 224 papers). Sphere size is related to the number of publications associated with a theme.

4.1.2. CE research between 2013 and 2015

Between 2013 and 2015, slightly more papers (227) were published than during the first 12 years of CE research. Despite the comparable number of publications, the number of themes grew from four to nine. This growth indicates the increasing differentiation of research foci. As illustrated in Fig. 4, two themes that relate to the R-strategies, reuse and recycling, emerged as separate themes. Besides "material flow analysis", which remained an isolated theme, a second assessment-related theme "life cycle assessment" appeared as an emerging theme. The period also witnessed a growing focus on waste (management).

The CE-related theme remained the largest (cF = 121), but its relative centrality as well as its density decreased. This change rendered it a basic theme during 2013 and 2015. While in the early research period, "sustainab*" still represented a motor theme (the only one), it disappeared in the second period as a separate theme and became part of the CE-related theme, which was furthermore expanded by the keywords "eco-efficiency" (8) "resource efficiency" (6). The theme of "industrial ecology[3]" remained in the basic category, indicating the continuing importance of such conceptual foundations in CE-research. The related concept of industrial symbiosis, however, split from the IE cluster and formed a new cluster with China. The most frequent keyword in this theme was again "China", thus illustrating the leading role played by China and the meso-level focus of CE-related research. Regarding the link between sustainability and CE research, one can

[3] However, it was renamed "China and industrial symbiosis" as industrial symbiosis was more frequently used than industrial ecology during this subperiod.

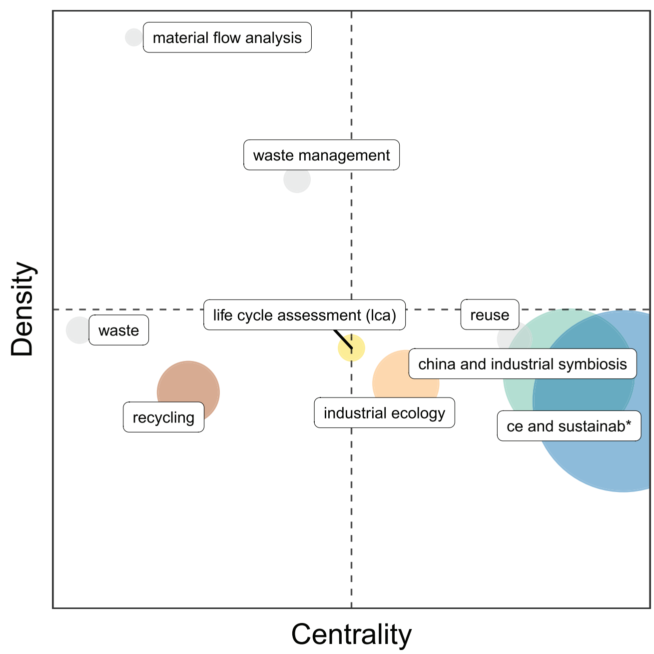

Fig. 4. Thematic map of circular economy research between 2013 and 2015 (n = 227 papers). Sphere size is related to the number of publications associated with a theme.

summarize this by saying that while environmental impact assessment, resource and eco-efficiency-related research emerged during this period, other environmental and social aspects related to sustainability continued to play almost no role. Moreover, recycling approaches dominated, while only seven papers referred to reuse.

4.1.3. CE research between 2016 and 2018

Fig. 5 shows the third thematic map for the years 2016–2018. In this period there was a sharp increase in the number of publications (227 to 1794), as well as in the number of themes (9 to 19). As can be seen, the

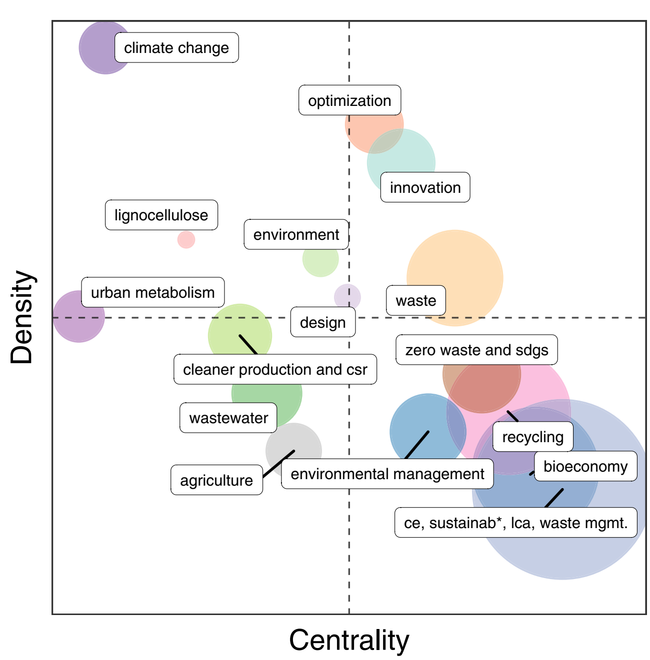

Fig. 5. Thematic map of circular economy research between 2016 and 2018 (n = 1723 papers). csr = corporate social responsibility, lca = life cycle assessment, sdgs = Sustainable Development Goals.

CE-related theme remained, by far, the largest theme during this acceleration phase in the field. The CE-related theme exhibited a cumulative frequency of 2148, followed by the themes “bioeconomy” (cF = 294), “recycling” (cF = 269) and “waste” (cF = 94). While remaining the most central theme, the relative density of CE continued to decrease, thus consolidating its role as a basic theme in the field. During this highly active period of research, a total of 83 keywords were part of the CE-related theme, with the highest keyword occurrences being for “circular economy” (921), “sustainab*” (210), “life cycle assessment” (103), “waste management” (57) and “resource efficiency” (49). Keywords referring to R-strategies of a higher order, i.e. “remanufacturing”, “repair”, “reuse”, were also part of this theme but only occurred 35, 7 and 28 times, respectively.

Except for “waste” and “recycling” all themes that were still separately represented in the period 2013–2015 (see Fig. 4) became part of the CE-related theme between 2016 and 2018. Conversely, the remaining 14 themes only emerged in the period 2016–2018. The second-largest theme was also incorporated into the category of basic themes and comprised research that is correlated with the concept of “bioeconomy” (cF = 294), such as food waste, biogas, anaerobic digestion or biorefinery. The remaining basic themes covered research related to “recycling” (cF = 269) (the only R-strategy forming a separate theme) “zero waste and SDGs” (cF = 49) and “environmental management” (cF = 45).

The category of motor themes was, in contrast to the preceding period, again, populated by four themes (“waste”, “innovation, “optimization” and “design”). However, compared to the basic themes, their cumulative frequencies only ranged from 94 (waste) to 7 (design). Seven of the newly emerged themes were classified as isolated (4 themes) or emerging (3 themes), with even lower cumulative frequencies than the “motor themes”, ranging from 36 (wastewater) to 5 (lignocellulose).

Furthermore, LCA (103) and MFA (22) remained the most frequently referred to assessment methods, while sustainability assessment, energy and substance flow analysis appeared only 5–7 times.

With regard to the CE-SD connection, one can see that during 2016–2018 the general descriptor “sustainab*” remained within the CE theme and that, in addition to this, and driven by the general growth in the number of publications, a greater variety of more specific sustainability topics began to appear across the different themes. However, with regards to their relation to the three dimensions of sustainable development, an almost exclusive emphasis on environmental and economic topics can be observed, with resource efficiency and eco-efficiency remaining central. This rather efficiency-driven focus has also been subjected to strong criticism (see Section 4.5). Only the keyword “corporate social responsibility” (7) directly refers to the social dimension of sustainability. While a few other keywords (e.g., education, sharing economy, consumers) at least indicate a social focus, they occur even less frequently.

4.1.4. CE research in 2019

Fig. 6 shows the final thematic map for the year 2019, a year in which almost as many papers (1648 papers) were published as in the preceding three years (1723). The number of themes, however, stayed the same (19). As can be seen, the CE-related theme remained the largest basic theme (cF = 2359) and its density, continued to decrease (slightly). This means that while a larger number of papers continue to refer to the CE, they refer less often to each other, rendering the internal connections in the CE theme rather loose. In comparison to 2016–2018, the top keywords in the CE-related theme, did not change significantly, nor did their distribution. Circular economy (874) remained the most frequent keyword, followed again by “sustainab*” (239), and “LCA” (85). Only the former, separate theme “recycling” (239) became part of the CE-related theme. The R-strategy “reuse” (42) and “remanufacturing” (31) and “repair” (6) also remained within the CE theme. “Bioeconomy” remained the second-largest basic theme,

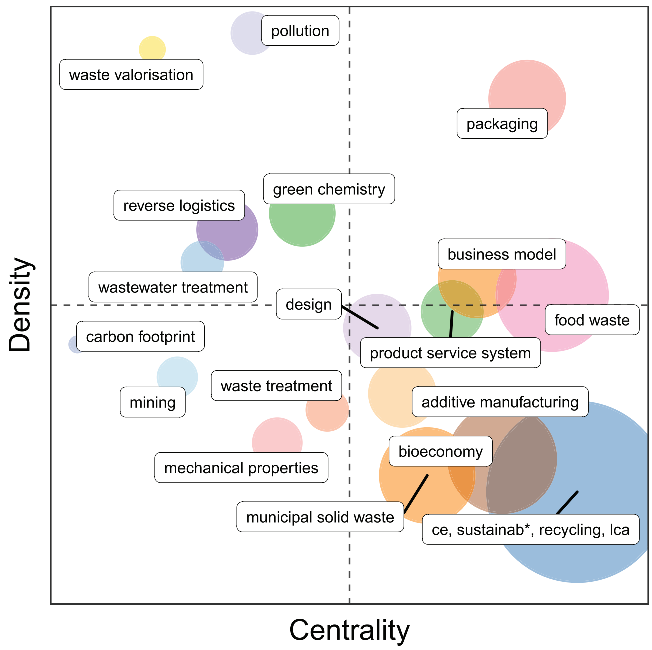

Fig. 6. Thematic map of circular economy research in 2019 (n = 1648 papers).

followed by "municipal solid waste".

In the category of motor themes, "food waste", emerged as the largest theme, and split away from the basic theme of "bioeconomy". The "design"-related theme remained small, and verged on becoming a basic theme. Another new motor theme emerged around "packaging" (cF = 54), which mainly relates to plastic waste and (bio) plastics. The last, newly emerging motor theme "business model" comprises sustainable business models, climate change and SDG-related topics.

The relative shares of the main assessment methods in the literature remained largely the same as those found in the previous period (LCA = 85 occ., MFA = 18 occ). However, one new theme emerged around "carbon footprint" (cF = 5). Additionally, "emergy analysis" (5) and "economic analysis" (5) began to appear as part of other themes.

No significant changes to 2016–2018 can be observed with respect to the CE-SD relationship, The general descriptor "sustainab*" (236) remains as part of the basic CE-related theme, as do seven other specific sub-concepts, of which "environmental sustainability" occurs most frequently (16) followed by "sustainable supply chain" (9), "sustainable consumption" (8) and "sustainable production" (7). The almost exclusive focus on environmental sustainability continues and indications of a specific emphasis on the social dimensions of sustainability even exhibit a decline in prominence. The previous social theme "corporate social responsibility", as well as direct references to consumers and education disappear. Except for other proxies such as "sharing economy" (7) and "stakeholder" (7) no direct references to social sustainability can be found in the 2019 body of literature.

4.2. Conceptual structure revealing the structural dynamics of CE research

Fig. 7 illustrates the conceptual structure of CE-related research based on the MCA and k-means clustering approach outlined in Section 3.2.2. As for the thematic maps in the previous section, the analysis was conducted on the full set of 3822 CE-related publications using keywords plus. However, in contrast to the time-sliced thematic mapping, the analysis of the general conceptual structure covers the entire period of research. Using a minimum degree of 60 (i.e., keywords that appeared at least 60 or more times), as a filter criterion in the MCA function of the "bibliometrix" package (Aria and Cuccurullo, 2017), provided a matrix of 2507 publications and 73 keywords. The data was pre-processed for the k-means clustering using an MCA, in which the first two dimensions explained 63.43% (Dim. 1 = 47.61%, Dim. 2 = 15.82%) of the total variance. The percentages represent adjusted eigenvalues following the approach of Benzécri and Greenacre (Greenacre, 2007). Given their comprehensibility, two-dimensional plots are usually the representations of choice (Greenacre, 2007). Dimensions 3 and 4 only explain 10.21% and 6.52% of the total variance and they did not add a significant explanatory value.

The results are interpreted based on the relative positions of the points and their distribution along the two dimensions of the coordinate system. Keywords that are more similar in their distribution over the publications are closer to each other (Aria and Cuccurullo, 2017). The closer a keyword is to the origin of the coordinate system, the closer it is to the average profile of the 3822 publications. Therefore, the further away a keyword is from the origin, the more strongly it differs from the average profile of CE research. Furthermore, the two dimensions divide the data in such a way that keywords/clusters which oppose each other on either one of the dimensions, exhibit diametrically opposed profiles.

As can be seen in Fig. 7, a total of twelve meaningful clusters were identified. Fig. B1, in Appendix B, additionally provides the topic dendrogram. The cluster comprising the keywords "circular economy" and "sustainab*" is the most central one, with the keyword "circular economy" being the closest to the origin of the coordinate system (i.e. the average profile).

The distribution of clusters along the x-axis (Dimension 1) suggests a distinction of CE-related research in terms of its focus on the life cycle phases, ranging from a beginning-of-life (BOL) focus, with the cluster A "design and innovation" at the most polar position, to an end-of-life (EOL) focus, with cluster L "waste incineration" at the opposing end of the axis. As can be seen, the BOL side of the spectrum reflects a focal company perspective as keywords such as supply chain management, manufacturing, product design are present, while the material extraction phase is neglected. The succession from a BOL to an EOL focus on Dimension 1 can also be observed when tracking, in a total of seven clusters along Dimension 1, the contexts in which "waste" is used. The general descriptor, waste, forms a cluster with industrial waste (G). Wastewater treatment and wastewater form two clusters related to biomass (D), to biogas, to fertilizer, and also to the general descriptor chemistry (H). Waste management forms a cluster (J), with environmental policy and plastic. The two right-most clusters K and L indicate a focus on waste disposal, waste treatment, solid waste, food waste, municipal solid waste, landfill and waste incineration.

Linking the twelve clusters to the 10-R Strategies[4] (Reike et al., 2018) another succession can be observed that resembles the hierarchy of CE value retention options. While keywords in the clusters A, B and C such as "design", "innovation", "product design", "supply chain management" or "manufacturing" relate to potential enablers for higher order CE value retention options, clusters towards the right-hand side of the coordinate system indicate a focus on lower-order value retention options such as recycling, recovery, waste treatment or even a focus on linear EOL-options such as disposal or incineration (clusters K and L).

The distribution of clusters along Dimension 2, which only explains about a third of the variance of Dimension 1, suggests a second division of the field into management and assessment-oriented research (clusters A, B,C, F, J), and technically-oriented research (clusters D, E, G, H, I, K, L). Whereas, the management-oriented clusters comprise several topics that were part of the basic theme "CE, sustainab*, LCA and waste mgmt." and the motor themes "innovation" and "design" (as seen in Fig. 5), the technically-oriented clusters relate to the emerging themes "agriculture", "waste water", and the motor theme "waste".

In regard to the CE-SD relation, the conceptual structure reinforces the findings described earlier, and also adds an additional perspective. As can be seen, the keyword "sustainab*" is part of the CE-related

[4] R0 Refuse, R1 Reduce, R2 Resell/Reuse, R3, Repair, R4 Refurbish, R5 Remanufacture, R6 Repurpose, R7 Recycle, R8 Recover, R9 Remine.

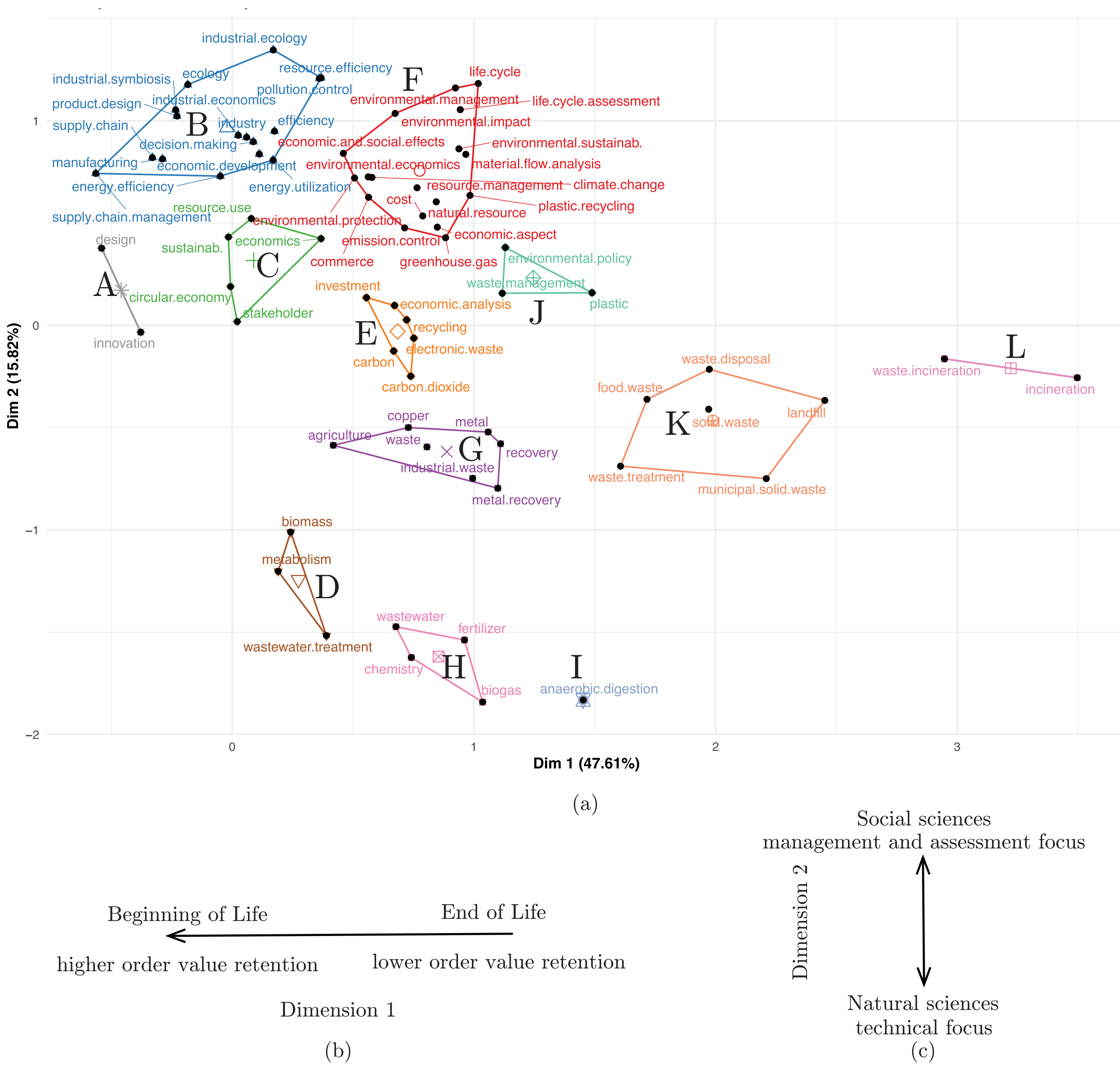

Fig. 7. (a) Conceptual Structure of Circular Economy research from 2000 to 2019. Clusters = 12, Min. degree = 60, A-L = cluster names, (b) Positive and negative centroid coordinates for dimension 1. (c) Positive and negative centroid coordinates for dimension 2.

cluster C that is the closest to the average profile - analogous to Figs. 5 and 6, in which it is part of the most basic theme. The other keywords in cluster C indicate a focus on resource use and stakeholders. Furthermore, general indications of the sustainability connotation are indicated by energy/resource efficiency, pollution control and ecology in cluster B, environmental management, economic and social effects, resource management or emission control in cluster F, and carbon dioxide in cluster E.

4.3. Top 20 discussed topics in CE research

As a final statistical analysis of the content of the papers, a correlated topic modeling (CTM) of the 3822 abstracts of CE research was fitted to contrast and expand on the previous, keyword-based analyses. In line with the model selection rationale outlined in Section 3.2.3, 20 topics were selected as being the most reasonable for the purposes of the present study. Fig. 8 illustrates these 20 topics in decreasing order of prevalence in the CE body of literature. The respective prevalence represents the topic's relative share within the full CE body of literature, i.e. its percentage share.

As can be seen, the first-ranked topic corresponds with the CE-related basic themes in Section 4.1, formed during the last four years of research. Topic 1 also exhibits the highest contribution of the word “CE” as can be seen in Fig. C2 in Appendix C. The second most prevalent topic comprises research on waste management and recycling. Topic 3 is related to the IE/IS and China-related research that formed the most central theme in the early years of CE research in Section 4.1.

Ranked 4th and 5th are topics that refer to material, production and products. In general, waste has a high contribution to 13 of the 20 topics (defined as being part of the top ten contributing words), followed by recycling (5 topics), which always co-occurs with waste (see Table C1 in Appendix C for an overview of this analysis). Remanufacturing defines Topic 16, which furthermore, is defined by the words supply, chain and processes. Reuse contributes insignificantly to

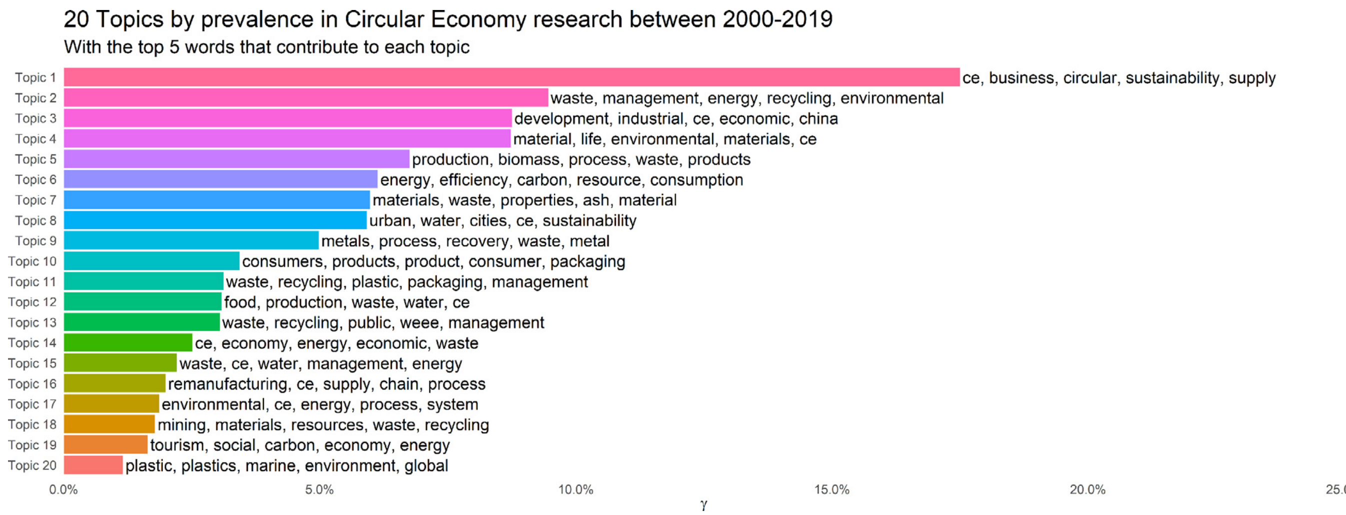

Fig. 8. 20 Topics in Circular Economy Research in order of prevalence. The labels give the seven words with the highest contribution to the topic. ce = circular economy, bms = business models. Prevalence refers to the topic's share in the analyzed body of 3822 papers.

Topic 19. Other value retention options of a higher order do not occur directly. However, two topics indicate a focus on potential enablers for such higher order value retention options: In the top 15 words contributing to Topic 1 (as can be seen in Fig. C2) references are made to (sustainable business) models and design, and Topic 10 is defined by the words consumers, consumption and behavior.

When comparing the findings of the CTM with the conceptual structure above, it can be observed that only Topic 1 relates to clusters A and B, and Topic 16 to cluster B, all of which are positioned at the "higher order value retention" end of the dispersion of clusters along Dimension 1 in Fig. 7b. The dominating waste, recycling and recovery-related topics, however, correlate with the clusters on the "lower order value retention" side of the spectrum. Furthermore, four Topics (7, 9, 13, 15) relate largely to the technically-oriented and four to the management-related clusters (Topics 2, 11, 13, 15) in Fig. 7a.

Finally, regarding the CE-SD relationship, the results of the CTM confirm the dominance of environmental considerations in CE research, with eight topics (2, 3, 4, 10, 13, 15, 17, 20) covering aspects related to energy, emissions, resources, materials and water. Regarding the economic dimension, it can be observed that the term "economic" contributes to four topics directly (8, 13, 14, 19) and that three additional topics, including the most prevalent one, furthermore refer to either business (1) or industry (3, 6, 14). In contrast to this, only in Topic 19, which is defined by the word tourism, is reference made to the word social. No other direct indications of a focus on social sustainability can be found.

Summarizing, one can thus say that, on the one hand, the CTM confirms the results of the previous two sections, as patterns similar to those in the thematic mapping in Section 4.1 (e.g., lack of social sustainability focus, the strong prevalence of research focusing on resource efficiency, waste management and recycling) can also be observed when analyzing the paper abstracts. On the other hand, it also expands upon and deepens the insights gained regarding the paper topics, as it was possible to identify three topics relating to higher order value-retention options (Topics 1, 10, 16). The following section presents the results of the historiographic analysis and thus provides a transition to the investigation concerning the semantics of the CE-SD relation.

4.4. Historiographic analysis of citations revealing key publications in ce research

For the historiographic analysis, the literature subset on CE and SD (n = 2149, see Fig. 1) was chosen (see Section 3.1). This revealed those papers that define, or make a decisive contribution to, the debate on sustainability in the CE context, and thus helped to answer research questions two and three. Based on the local citation score (LCS), a historical direct citation network was created. LCS measures how many times a paper included in the collection (in this case: 2149 papers on CE and SD) has been cited in other papers in the collection. To keep the graph lucid, and to ensure that subsequent content analysis remained manageable, only the top 30 papers were selected for depiction. The result is shown in Fig. 9. In total, the top 30 papers have an LCS ranging from 306 (Ghisellini et al., 2016) to 42 (Elia et al., 2017). In Fig. 9, the size of the nodes depicts the respective number of citations. The bigger the node, the higher the LCS of the respective paper. A table including the 30 papers and the respective LCS is included in Appendix D (Table D1). In general, the increase in the rapidity of publication is also revealed in this analysis. As can be seen, 20 of the 30 papers were published between 2016 and 2018. Thus, two thirds of the papers were published in the last 4 years of the analysis and yet received a sufficient number of citations for inclusion in the network. This was not the case for any paper from 2019. Consequently, the verticality of the network increases in order to include the increasing number of papers. Simultaneously, the speed of direct citations is increasing, as is reflected in the shorter, and from 2017 onwards, vertical connections between papers.

Some papers have a specifically high importance within the network, namely Andersen (2007), and Geng and Doberstein (2008) with 11 citations, and Mathews and Tan (2011), and Geng et al. (2012), with 9 citations each, within the top 30 papers (intra-network citations, INCs) (represented by the edges between the nodes). This is a high value given that the highest INC is potentially 29 from which the previously published papers have to be deducted. Furthermore, one can see that these papers have been cited continually throughout the whole period, and have thus clearly remained influential over the years. They may thus be considered the reference papers around which the circular economy and sustainability discussion is built. On the other hand, one paper (Linder and Williander, 2017) has a maximum of one connection (either referring or referred to), while there is no completely isolated paper in the network. Additionally, the relative LCS was calculated, depicting the percentage of local citations compared to global citations (all citations that are indicated in the respective databases). The result is included in Table D1 in Appendix D. The relative local citation score ranges from 59.52% (Andersen, 2007) to 30.41% (Haas et al., 2015), with a median value of 43.32% and an average value of 43.74%. A higher relative LCS indicates that the paper is more commonly cited within the literature on SD and CE (and has hence within a specific research stream as target), whereas a lower relative LCS indicates either

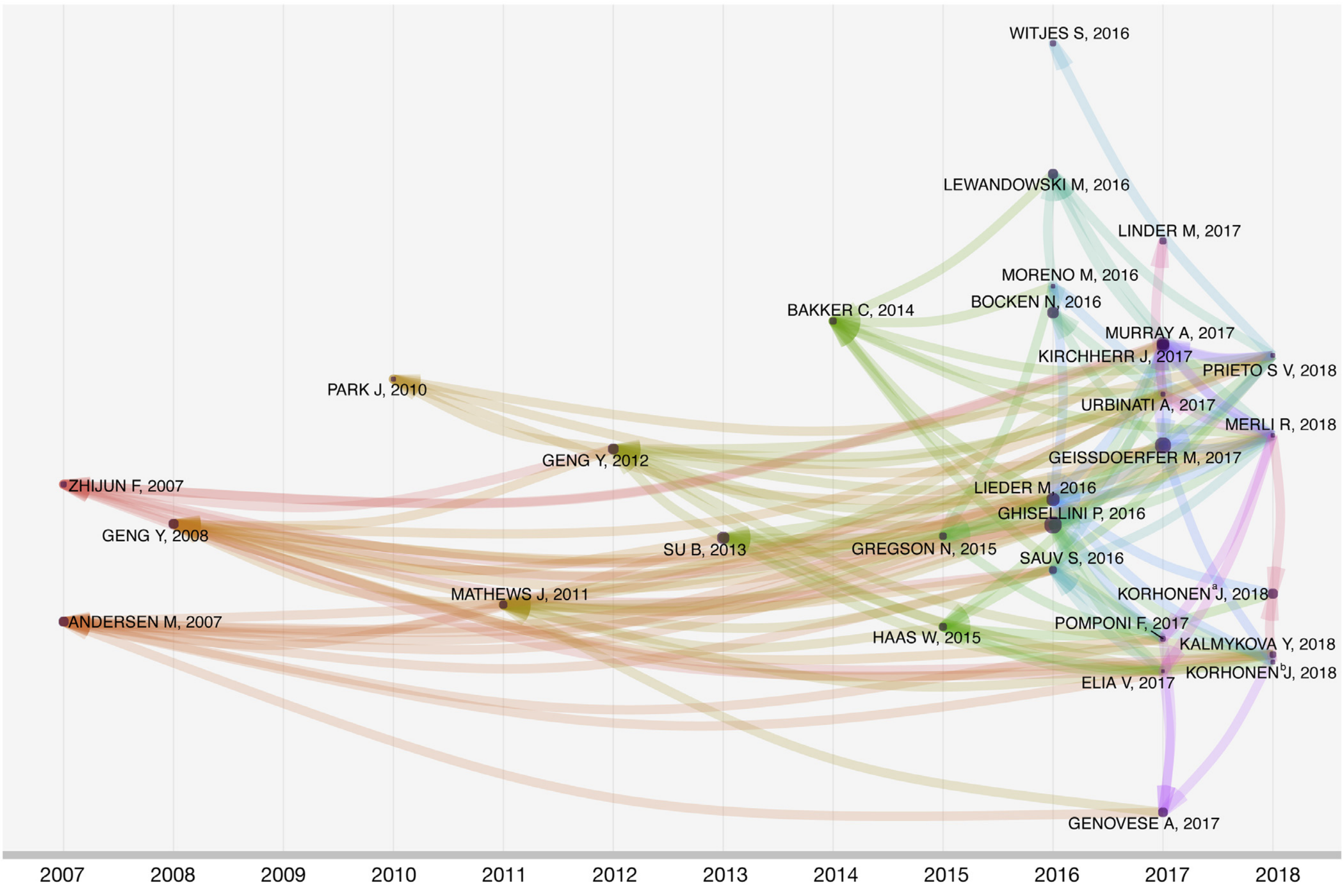

Fig. 9. Historical Direct Citation Network of the top 30 papers in the circular economy and sustainability literature and their citation relationships.

dissemination to other research streams or that a paper itself has connections to other fields of research.

4.5. The semantics of CE and sustainability

To complement the previous quantitative bibliographic analysis of circular economy, and circular economy and sustainability, a qualitative content analysis was also performed. This entailed identifying the 30 most influential papers from the circular economy and sustainability literature, i.e. those with the highest local citation score (see Section 4.4), and analyzing the key insights on the relationship between CE and sustainability as found in the guiding papers. The papers were analyzed according to different categories linking CE and sustainability, and the respective semantics. The following categories were chosen, due to their appearance in Sections 4.1-4.3 as part of the sequential mixed methods design (inductive category creation), and due to their direct relation with the research questions (deductive category creation): (i) *the inclusion of sustainability pillars* (directly related to RQ 2), (ii) *CE and sustainability assessment*, in order to identify how CE was assessed in terms of sustainability, and how this was perceived (Sections 4.1.1 to 4.1.4, and related to RQ3), (iii) *value retention options*, as defined by Reike et al. (2018) as a proxy for circular strategies, and due to their appearance across all Sections 4.1 to 4.3, and the high prominence of R-strategies in the CE debate, and (iv) *design and innovation*, due to their increasing importance in the literature, as observed in Section 4.1.3, and due to their position at the pole of BOL in Fig. 7.

4.5.1. The inclusion of sustainability pillars

This section considers the inclusion of the social, the environmental, and the economic pillars of sustainable development. Comparable to the quantitative analysis, the "sustainab*" subset of the CE literature also places a focus on the economic and the environmental dimensions. Most papers include the social dimension to a certain extent, yet the focus remains more environmental or economic. Terminology partially includes the word "social", yet it is also used as a prerequisite for the economic dimension, such as "social consumption system", as used by Zhijun and Nailing (2007). Other notions on the social dimension include the need for a change in social behavior (corresponding to topic 10 in Fig. 8) and perception of quality, in order to increase acceptance of the higher ranking R principles, such as repair, refurbish, remanufacturing (Bakker et al., 2014; Sauvé et al., 2016). The direct correlation with the R strategies found here complements the quantitative results, where the role of the consumer is more narrowly discussed (if at all). Behavioural change has been associated with adequate governmental policies (Prieto-Sandoval et al., 2018; Urbinati et al., 2017b). While a number of authors have highlighted the need for inclusion of social sustainability in the CE debate (e.g. Geng et al., 2012; Zhijun and Nailing, 2007), there has been no sign of it becoming central over time. On the contrary, the lack of a social dimension has been explicitly commented on in recent publications (Ghisellini et al., 2016; Pomponi and Moncaster, 2017). Murray et al. – the only paper mostly covering a societal perspective – noted, that CE *"is virtually silent on the social dimension"* (2017, p. 376), and added that the mechanisms of how CE leads to more social equality and equal opportunities for everyone remain unclear (ibid.). Nevertheless, social matters have gained attention within the CE debate in recent years (Merli et al., 2018). This focus is tightly linked to the area in which CE is embedded, namely in production and consumption systems. That is, while organizational strategies and production are rather environmentally coined, the consumption phase as social and societal issue per sé and its interrelatedness with a functioning CE is increasingly being recognized

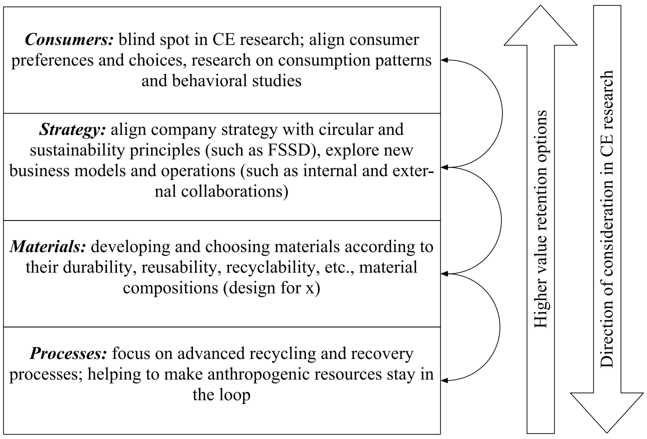

Fig. 10. Framework of CE research levels, FSSD = Framework for Strategic Sustainable Development.

in the debate, especially when considering the sharing economy and policy interventions (Korhonen et al., 2018b; Prieto-Sandoval et al., 2018). This trend has also been observed in the thematic maps (Fig. 6), where product-service-systems and packaging (which is closely related to consumption systems as seen in Fig. 8) appear as topics in 2019.

The inclusion of the economic and the environmental dimensions are more prevalent. Kirchherr et al. (2017), who analyzed 114 definitions of CE, amongst other things, regarding their inclusion of sustainability dimension, as well as Sections 4.1 to 4.3, confirmed this. From a semantic perspective, the necessity to internalize negative environmental externalities is mentioned across the whole time span (Andersen, 2007; Sauvé et al., 2016). The idea of mutual benefit between the economic and the environmental dimension arising through a CE is discussed to a large extent (Elia et al., 2017; Sauvé et al., 2016). However, over time, scholars begin increasingly to question this narrative. While between 2007 and 2014 the papers mainly focused on how to achieve a CE that inherently benefits the environment (Geng and Doberstein, 2008; Mathews and Tan, 2011; Park et al., 2010), several papers published since 2017 explicitly address shortcomings, limits, and uncertainties with respect to CE and environmental or economic sustainability. For example, Linder and Williander (2017) reported that circular business models entail a significantly higher level of uncertainty compared to linear business models, since their value proposition and economic profitability depends on recirculation activities that happen after the use phase, and hence entail a temporal dimension, a dimension which linear business models need not consider. Furthermore, Kalmykova et al. (2018) claimed that CE is rather more focused on eco-efficiency than on eco-effectiveness, while Korhonen et al. (2018a), in line with this, defined six limitations for environmental sustainability in a CE, including lock-in and rebound effects (see Section 4.5.3). This more critical view is reflected in other recent publications referring to a potential CE rebound (e.g. Bocken et al., 2016; Ghisellini et al., 2016; Merli et al., 2018). Altogether, Geissdoerfer et al. (2017) depicted different relations between sustainability and CE, from conditional, to trade-off. Aside from sufficiency-related topics, recent publications also aim at a systems and a societal perspective of CE, requiring a fundamental change of production and consumption systems (Kirchherr et al., 2017; Korhonen et al., 2018a), for example, by including society's role in a sharing economy (Korhonen et al., 2018b). This observation is reflected in the diffusion of keywords and topics into more societal spheres observed in Section 4.1.

Summarizing, it has been found that social aspects remain underrepresented in the CE debate, while the win-win narrative depicting the environmental and economic benefits of a CE has become the subject of increasing criticism.

4.5.2. CE and sustainability assessment

Sustainability assessment is treated in numerous ways. Some authors proposed existing methods to assess sustainability within CE, such as life cycle assessment (Andersen, 2007). Others proposed new methods: for example, Zhijun and Nailing (2007) proposed the integration of an economic index, a green development index, and a human development index. Geng et al. (2012) evaluated the Chinese indicator set on CE. Elia et al. (2017) analyzed the applicability of several index-based methods for assessing CE strategies on the micro, *meso*, and macro levels. Furthermore, some authors mentioned specific circularity indicators (Lieder and Rashid, 2016; Pomponi and Moncaster, 2017). Several papers applied assessment methods in a circular context: Haas et al. (2015) used material flow accounting at the macro level to assess global material flows, while Hu et al. (2011) applied MFA to the utilization of leather tannery waste, and Bakker et al. (2014), and Genovese et al. (2017), applied a LCA and hybrid LCA, respectively. As indicated, for example, in Section 4.1, LCA and MFA play a dominant role when assessing sustainability in a circular context, and this is reflected in the CE and SD literature sample. These methods are also explicitly recommended in the sample (see Elia et al., 2017 for LCA, and Kalmykova et al., 2018 for MFA), alongside the use of wider indicator sets (Geng et al., 2012). Nevertheless, the absence of social issues in these methods, as well as the narrow indicator use in some contexts (Ghisellini et al., 2016; Pomponi and Moncaster, 2017) indicate a lack of consensus and standardization regarding the suitability of specific assessment methods (Su et al., 2013). Apart from that, there appears to be little application of circularity indicators or indicator sets. Korhonen et al. (2018a) stated that the mere observation of material flows is insufficient for comprehensive understanding of the sustainability implications of CE efforts, and Bocken et al. concluded that *"methods for assessing the environmental, social, and economic sustainability of circular products and business models will need to be developed"* (2016, p. 317) .

Consequently, while the only relevant assessment methods in a broader CE context are LCA and MFA (correlating with the findings in Section 4.1), a more nuanced debate around suitability, applicability,

Table A1
Themes in the research period 2000–2012. Freq = cumulative frequency per theme.

Name	Freq	Words	Centrality	Density
circular economy	119	circular economy 119	29.96961	314.4024
material flow analysis	9	material flow analysis 9	4.847828	330.2083
China and industrial ecology	81	china 23 industrial ecology 19 eco-efficiency 11 industrial symbiosis 10 eco-industrial park 9 cleaner production 9	81.83623	285.1617
sustainab*	29	sustainab* 29	55.0107	318.4353

Table A2
Themes in the research period 2013–2015. Freq = cumulative frequency per theme.

Name	Freq	Words	Centrality	Density
china and industrial symbiosis	46	china 21 industrial symbiosis 20 eco-industrial park 5	43.6554	347.8345
life cycle assessment	6	life cycle assessment 6	29.647	383.7449
CE and sustainab*	121	circular economy 84 sustainab* 23 eco-efficiency 8 resource efficiency 6	86.00956	322.4007
recycling	12	recycling 12	23.05838	332.5826
industrial ecology	13	industrial ecology 13	30.29816	339.948
waste	6	waste 6	20.14539	390.5556
reuse	7	reuse 7	33.46088	388.1696
material flow analysis	5	material flow analysis 5	22.71843	844
waste management	6	waste management 6	26.6451	453.2258

and methodical focus is arising in influential literature, including a debate around indicator sets at different CE levels. So far, however, applications of such new perspectives continue to be almost non-existent, and LCA and MFA have remained the methods of choice in the sample analyzed.

4.5.3. R-strategies

With respect to the value retention options, it was observed that terminology focuses for the most part on the 3 Rs (reduce, reuse, recycling) (Geng and Doberstein, 2008; Ghisellini et al., 2016; Su et al., 2013) and sometimes on the 4 Rs (3 Rs + recover) (Kirchherr et al., 2017; Murray et al., 2017). This observation has been slightly different in Sections 4.1 to 4.3, where mostly recycling and reuse (e.g. Fig. 4), and to a certain degree remanufacturing (Section 4.3) and recovery (Fig. 7) explicitly shaped the CE debate. Within the analysis, a non-uniform use of the value retention options was observed. The term reduce referred to both the absolute reduction of material use (such as throughput) (Ghisellini et al., 2016; Korhonen et al., 2018a), as well as to the reduction of environmental impacts or waste generation of any kind as a consequence of improving circular behavior, and could also include increased recycling (e.g. Genovese et al., 2017). The terminology was somewhat blurry here. The same was observed for reuse. Some authors referred to reuse at the product level (Bakker et al., 2014; Bocken et al., 2016), others at the material and substance level (Mathews and Tan, 2011; Su et al., 2013). This blurs the distinction between reuse and recycling. The terms repair, refurbishment, and remanufacturing appeared mainly at the product level, and were referenced as key strategies in more circular activities at this level (Lewandowski, 2016; Lieder and Rashid, 2016). They were central in papers dealing with business models (innovation) or in those with a focus on product design (Bocken et al., 2016; Lewandowski, 2016; Moreno et al., 2016; Urbinati et al., 2017b). Consequently, value retention options were closely connected with early life cycle stages (see also Section 4.5.4). Bakker et al. (2014) subsumed such strategies under the umbrella term reuse, while Ghisellini et al. (2016) only subsume repair explicitly under reuse. The term recovery, also appeared in different connotations: First, as energy recovery, which in general was perceived as a low value retention option (Gregson et al., 2015; Lewandowski, 2016). Second, as material recovery, which was either defined as an umbrella term for value retention options such as reuse, repair, etc. (e.g. Witjes and Lozano, 2016), or as a recovery operation in which material is prevented from going to landfill (Ghisellini et al., 2016). For the latter, recovery would be a prerequisite for subsequent value retention options. Furthermore, the terms re-purpose and re-mine were hardly ever mentioned. Gregson et al. (2015), and Lieder and Rashid (2016) refer to re-mining with regards to rare earth metals and resource scarcity. Gregson et al. (2015) discuss re-purposing products after a use phase. The term re-purpose was also connected with re-purposing materials for applications other than the original one, a process corresponding to recycling (Bakker et al., 2014; Haas et al., 2015). Similar to the terms re-mine and re-purpose, refuse was also almost non-existent, although the borders between refuse and reduce are rather fluent: the consumer side of refuse is implicitly addressed through the need for reducing consumption, while the producer side implies reduction in the use of hazardous production inputs, such as toxic chemicals (e.g. Lewandowski, 2016; Witjes and Lozano, 2016).

To sum up, integration of 3Rs (and sometimes 4Rs) dominates observations in the sample, with there being an additional, product-centric focus for repair, refurbish, and remanufacture. At the same time, refuse, re-purpose, and re-mine were hardly mentioned. Additionally, The sample terminology was found to be somewhat blurry with regards to (i) application and with regards to (ii) the level at which a respective principle is located.

4.5.4. Design and innovation

The sample revealed a variety of topics related to design: adequate policy design, design of (sustainable) supply chains for circularity, system design, design of eco-industrial parks, design of the production-consumption system, product design and eco-design (in terms of energy efficiency, and also in a broader sense, such as in design for the environment) were the most central. While design as a concept already played a role in 2007 (Zhijun and Nailing, 2007), the four papers mainly occupied with design issues were all published from 2014 onwards (Bakker et al., 2014; Bocken et al., 2016; Lewandowski, 2016; Moreno et al., 2016). This is mirrored in the increasing role of design in Section 4.1 and as distinct cluster of its own in Section 4.2. Two of the papers specifically focused on product design (Bakker et al., 2014; Bocken et al., 2016), two on business models (Bocken et al., 2016; Lewandowski, 2016), one establishes a framework for circular design (considering several business models for circularity) (Moreno et al., 2016). Their commonality lies in a focus on the early life cycle stages, which parallels the observations found in Section 4.2. In the case of products, design is mainly related to targeting higher value retention options, exemplified by design for x approaches (such as design for remanufacturing, for disassembly, repair, etc.) (Bakker et al., 2014; Bocken et al., 2016; Moreno et al., 2016). Also, discussion of design for sufficiency, and especially design for longer product life in order to counteract planned obsolescence, is found e.g. by Bakker et al. (2014) and Moreno et al. (2016). Here, several authors stress the importance of aligning product design with adequate business model design, in order to ensure that original design intentions are met (Bocken et al., 2016; Moreno et al., 2016; Urbinati et al., 2017b) since otherwise, their

Table A3
Themes in the research period 2016–2018. Freq = cumulative frequency per theme.

Name	Freq	Words	Centrality	Density
bioeconomy	294	bioeconomy 25 food waste 24 biogas 22 anaerobic digestion 21 renewable energy 17 biomass 17 energy 17 biorefinery 16 bioenergy 15 pyrolysis 12	158.8003	210.3305
wastewater	36	wastewater 13 adsorption 7 valorization 6 textile 5 compost 5	21.19158	394.1831
urban metabolism	18	urban metabolism 10 nutrient recovery 8	9.725731	459.5833
recycling	269	recycling 129 e-waste 15 weee 15 recovery 13 packaging 11 fly ash 10 plastic 9 leaching 7 mining 7 extended producer responsibility 7	85.15992	337.2262
optimization	23	optimization 12 sharing economy 11	26.60038	772.2944
CE, sustainab*, LCA, waste mgmt.	2148	circular economy 912 sustainab* 210 life cycle assessment 103 waste management 57 resource efficiency 49 industrial ecology 49 industrial symbiosis 42 china 38 remanufacturing 35 reuse 28	288.5102	72.21309
cleaner production and CSR	28	cleaner production 8 corporate social responsibility 7 closed loop 7 cradle to cradle 6	20.31443	456.165
agriculture	21	agriculture 9 value chain 7 economy 5	21.62816	247.7707
environmental management	45	environmental management 8 urban mining 8 material flow 7 mechanical properties 6 characterization 6 construction and demolition waste 5 indicators 5	64.42792	282.2692
environment	10	environment 10	23.74772	496.7708
lignocellulose	5	lignocellulose 5	14.7721	530.2381
waste	94	waste 41 policy 10 manufacturing 9 efficiency 8 case study 8 resource 7 water 6 steel 5	73.60142	496.6013
design	7	design 7	24.96001	475.9921
climate change	19	climate change 13 sustainable agriculture 6	10.20401	1078.07
zero waste and SDGs	48	zero waste 13 resource productivity	75.75905	402.684

(*continued on next page*)

Table A3 (*continued*)

Name	Freq	Words	Centrality	Density
innovation	33	10 sustainab* goals 7 system dynamics 7 environmental sustainab* 6 material 5 innovation 17 collaborative consumption 6 governance 5 education 5	42.81813	662.2135

contribution to a sustainable CE can be limited or even negative. A holistic approach to design in CE is considered in more recent reviews (Kalmykova et al., 2018; Merli et al., 2018).

Consequently, while design plays a versatile role in the sample, its main focus from 2014 on, is on the product level and on adequate embeddedness in a business model.

With respect to innovation, from 2007 until 2014, a focus was set on technological innovation for the circular economy, including a discussion of the appropriate regulatory framework for stimulating R&D and investment in innovative CE activities (Prieto-Sandoval et al., 2018; Su et al., 2013). Furthermore, Geng and Doberstein (2008) included the public perspective by mentioning the necessity of innovative programs for public acceptance of CE activities and the potential unwillingness of government agencies to implement such programs. From 2015, innovation expanded to the managerial literature, where technological innovations in order to become feasible needed to be embedded in business model or service innovations (Bocken et al., 2016). Apart from that, bottom-up forms of innovation, such as open innovation or grassroots movements were named, thereby recognizing the role of the public and of citizens in a CE – albeit to a rather limited extent (Pomponi and Moncaster, 2017). Furthermore, Korhonen et al. (2018b) calls for capability development for radical innovation in order to cope with the desired effects of a CE, and Prieto-Sandoval et al. (2018) see mainly cyclic and regenerative forms of eco-innovation (which are both eco-centric perspectives on innovation) as suitable for a CE that follows sustainability principles. The potential scope of innovation with respect to a CE were structured by Witjes and Lozano (2016), using the terms organizational, social, and technological innovation, whereby all these forms need to complement each other in a CE transition.

To sum up, the sample covers innovation on numerous levels and with different approaches, and discussion continues to evolve around which type of innovation can be applied in practice, and what exactly is necessary to achieve an effective transition towards a circular economy.

5. Discussion

In the following, the findings are contextualized within the current CE debate and related to the research questions.

5.1. Research question 1

With regards to the first research question - (1) What research streams, concepts and topics can be distinguished in the field of circular economy, from a longitudinal perspective? – The present study has been able to deepen and specify findings from previous bibliometric CE reviews in various ways. Algorithm-based clustering and topic modeling approaches provide a reproducible and transparent structuring of CE research, one that is capable of taking the temporal dimension into consideration. It thus proved possible to significantly expand upon previous findings and to place them in a new and updated context. For instance, while Homrich et al. (2018) estimated two clusters in CE research (one related to industrial symbiosis in a Chinese context, and one to supply chains, material closed loops and business models) the present study finds that the field is much more diverse. As the thematic mapping shows, research from 2000 to 2012 was indeed largely rooted in IE/IS (Saavedra et al., 2018) and focused on the Chinese context (Cui and Zhang, 2018; Türkeli et al., 2018). However, the roots became much looser from 2013 onwards and especially between 2017 and 2019 (the exponential growth phase), with the additional emergence of many more environmental and economic themes. In relation to the growing thematic diversity in CE research, the present study further reveals that the conceptual structure of the field corresponds, along one dimension (Dim. 1), to the hierarchy of value retention options (10Rs) described by Reike et al. (2018), while along the second dimension (Dim. 2) a succession from management to technically-oriented research can be seen.

When comparing the qualitative (4.5) with the quantitative findings (Sections 4.1-4.3), it becomes apparent that the theoretical and conceptual debate, as reflected by the 30 key publications studied, is one which is diverse, self-reflective and conceptually progressive. The mainstream in CE research, however, as indicated by the quantitative analyses, can be considered as being rather narrow and despite its rapid growth in terms of research output, it is only slowly changing in terms of focal diversity. For instance, in terms of the topics recently emerging in CE research, one can observe a growing dichotomy between the fields of optimization, waste and efficiency-related work, on the one hand, and those of innovation and business model-related work, on the other hand. This can also be seen in the motor themes described in Sections 4.1. While the absolute number of occurrences of design, innovation and business models remains low, waste-related topics occur by an order of magnitude more often, and this is reflected in their increase in relative prevalence in the body of literature studied.

5.2. Research question 2

Regarding the second research question - (2) What is the role of sustainable development in the circular economy research debate? – this study reveals, in conformance with the findings of Geissdoerfer et al. (2017), that CE research and sustainable development, from the perspective of the quantitative analyses (Sections 4.1-4.3), tend to form a subset relationship. This means that while sustainability research addresses the area of economic and environmental issues, social topics remain underrepresented or are even neglected. Even though the semantic analysis reveals that this has been a clear point of criticism throughout the observed time period, the problem of how the incorporation of social and consumption-based issues may be achieved remains largely unresolved. The transition to CE needs to involve all societal actors since it is not only a question of raising general levels of acceptance, but also of promoting wide-reaching changes in production and consumption patterns. Furthermore, the present study revealed, in a quantitative fashion, the dominance of waste management and recycling solutions that have already been

Table A4
Themes in the research period 2019. Freq = cumulative frequency per theme.

Name	Freq	Words	Centrality	Density
CE, sustainab*, recycling, LCA.	2360	circular economy 874 sustainab* 239 recycling 118 life cycle assessment 85 waste management 80 waste 47 industrial ecology 35 reuse 33 industrial symbiosis 33 resource efficiency 32	449.8339921	103.7569576
product service system	20	product service system 8 durability 7 life cycle 5	62.71409616	368.3170996
business model	45	business model 15 climate change 13 sustainable business model 6 sustainab* goals 6 contamination 5	74.51913228	451.4412603
bioeconomy	156	bioeconomy 19 biomass 17 biorefinery 17 pyrolysis 15 energy 11 microalgae 10 adsorption 10 bioenergy 10 biofuel 9 extended producer responsibility 6 biochar 6 biotechnology 6	112.5922025	212.5504757
food waste	178	food waste 25 anaerobic digestion 25 renewable energy 19 biogas 18 phosphorus 11 digestate 8 manure 8 critical raw material 7 waste valorization 7 heavy metal 7	233.1431314	426.0018525
waste treatment	13	waste treatment 7 nutrient recovery 6	33.3208139	298.0371315
carbon footprint	5	carbon footprint 5	10.39381026	350.8888889
waste valorisation	7	waste valorisation 7	15.58272254	806.7619048
mining	12	mining 7 exergy 5	15.69862627	328.9047619
green chemistry	31	green chemistry 11 sustainable agriculture 5 system thinking 5 catalysis 5 zeolite 5	29.40676408	592.4141414
mechanical properties	17	mechanical properties 7 cement 5 valorisation 5	27.94889632	236.6866448

(*continued on next page*)

Table A4 (*continued*)

Name	Freq	Words	Centrality	Density
additive manufacturing	28	additive manufacturing 6 product design 6 waste recycling 6 3d printing 5 waste plastic 5	39.51872329	339.1960784
municipal solid waste	95	municipal solid waste 21 resource recovery 15 energy recovery 11 valorization 9 sewage sludge 9 municipal waste 7 gasification 7 zero waste 6 sustainable 5 waste to energy 5	44.32935715	208.4008295
design	33	upcycling 6 design 6 end-of-life 6 transition 5 batteries 5 food security 5	42.4404476	359.6801347
reverse logistics	26	reverse logistics 13 weee 8 competitive advantage 5	23.73577138	583.2809484
pollution	13	pollution 8 material 5	25.11638879	820.479798
packaging	47	packaging 14 plastic 14 plastic waste 13 bioplastic 6	172.0180946	738.4062024
wastewater treatment	13	wastewater treatment 8 carbon dioxide 5	21.3118378	470.5952381

reported on by other researchers, albeit on a qualitative level. The study also revealed the EOL focus and somewhat blurry connotations associated with several higher-ranking value retention options (especially reduce and reuse; see Section 4.5.3). In light of the potential pitfalls that can be caused by CE rebounds[5] (Figge and Thorpe, 2019; Zink and Geyer, 2017), negative sustainability outcomes cannot be entirely ruled out. Such negative sustainability effects of CE measures, would alter the CE-SD relationship, making it more selective in character, and possible pushing it more in the direction of explicit trade-offs (Geissdoerfer et al., 2017).

In this context, the emergence of design and innovation issues in recent years is therefore positive as it serves to bring connections to consumption patterns, systems, and business models, more to the fore. However, the application, diffusion and enabling patterns of CE activities, as well as the quantifiable sustainability implications and their wider impact on economic reality, still need to be analyzed (see also subsequent paragraph). For the sustainability assessment of CE activities, typical environmental assessment methods (MFA, LCA) dominate in both the quantitative as well as the qualitative analysis. However, despite their importance when attempting to detect possible trade-offs or rebound effects, their suitability for CE remains the subject of intense discussion, and a whole range of circularity indicators or indicator sets e.g., (Parchomenko et al., 2019; Pauliuk, 2018) are now in the pipeline. To date, the numbers of such applications remains negligible (Stumpf et al., 2019).

5.3. Research question 3

Concerning the third research question - (3) Which papers define the debate on a circular economy and on sustainable development? – first, a historical citation network was created. The 30 most frequently cited papers from the CE and SD literature were identified, and their relationships were depicted. The network revealed four reference papers (Andersen, 2007; Geng and Doberstein, 2008; Mathews and Tan, 2011; Zhijun and Nailing, 2007), and was able to show that some papers are mainly cited within the observed literature stream (higher relative LCS), whereas others showed stronger tendencies for diffusion into other streams (lower relative LCS). The subsequent qualitative analysis confirmed the main findings from the quantitative analysis on the CE literature. However, it was observed that the identified shortcomings in CE research, e.g. the lack of a holistic approach to SD and, in particular, the absence of a social dimension, are by no means recent findings. In fact, authors such as Andersen (2007), Zhijun and Nailing (2007), and Geng and Doberstein (2008) were already arguing for a renewed sustainability assessment in a CE context, and for the vigorous inclusion of social and policy innovations in order to increase public acceptance and participation in CE activities. However, such calls for inclusion have become more frequent in recent years. Apart from that, a more detailed and versatile discussion on other concepts around the CE (e.g. business models, sharing economy models) was found, including discussion of respective barriers and shortcomings.

[5] Five out of the 30 most influential papers also referred to potential CE rebound effects.

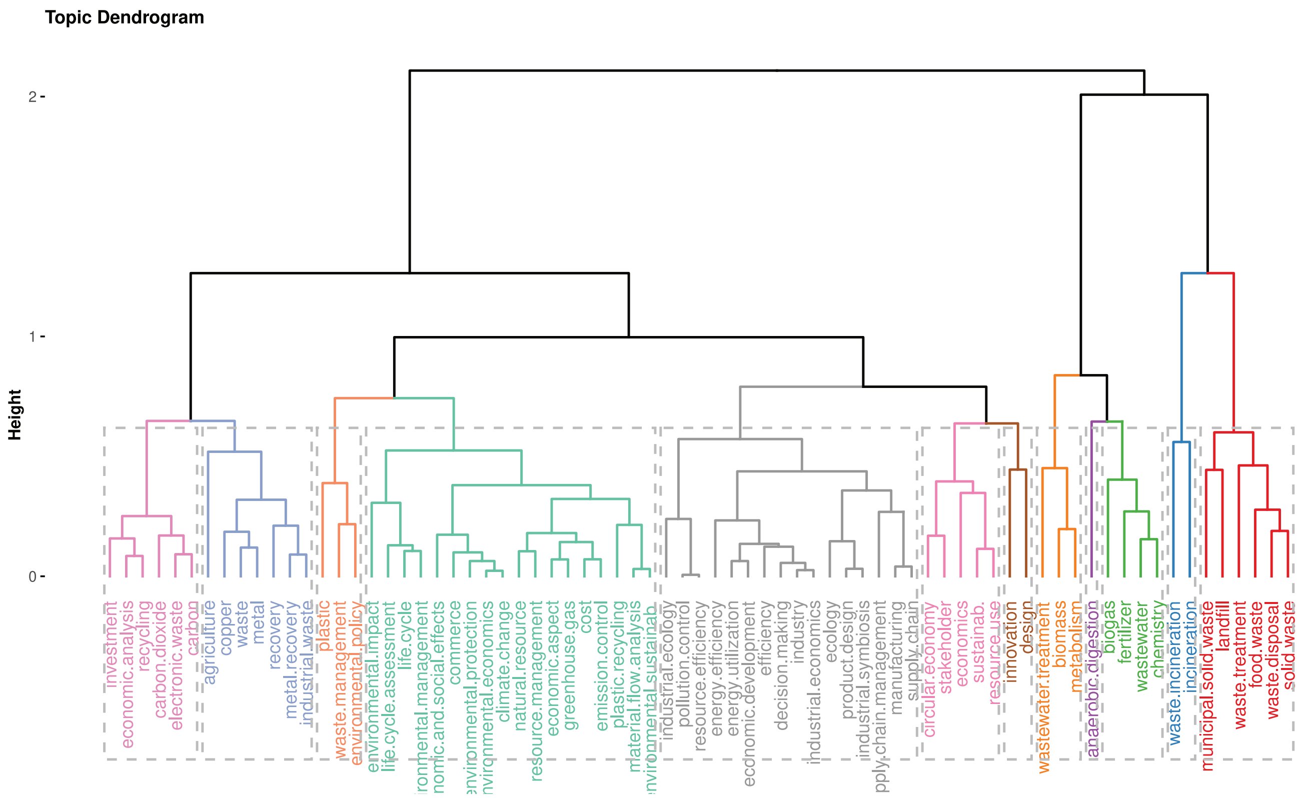

Fig. B1. Topic Dendrogram of the 12 keyword clusters identified in the circular economy literature between 2000 and 2019.

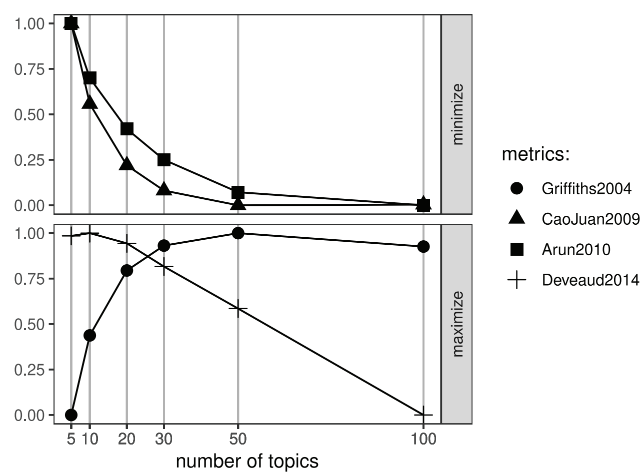

Fig. C1. Estimation of the optimal number of topics using the” LDAtuning” R package.

5.4. Synthesis

Fig. 10 provides a framework for summarizing the results of the present study. It consists of four levels (consumers, strategy, materials, processes), all of which need to be combined in a holistic CE approach (represented by the arrows connecting the levels). Technical processes form the base level, since this is where most recycling or recovery operations, or sourcing activities such as mining, occur (see Sections 4.1 - 4.3). The next higher level is the material level. The present analysis revealed that a variety of materiality groups have emerged. There are specific materials, such as plastics or metals (Sections 4.1-4.3), material streams, such as food waste (Section 4.1.4), and different approaches to dealing with materials (Section 4.2). Furthermore, it was found that these approaches need to be embedded in overarching strategies, and to be complemented with adequate (environmental and social) management practices (see Sections 4.1, 4.3 and 4.5) (level “Strategy” in Fig. 10). Established frameworks such as the Framework for Strategic Sustainable Development (FSSD) with its principle-based definition of sustainability boundaries, may be used as a robust guideline to integrate sustainability issues on the strategic level (Broman and Robèrt, 2017). Lastly, there is the level of consumers. Throughout the present study, this level was identified as being underrepresented, although there were some exceptions (Section 4.3). The two upper levels, in particular, are decisive in determining whether a CE is to be seen as something characterised by specific materials, or as an overarching system, requiring wide-reaching, social innovation. While the hierarchy with respect to the value retention options places consumers at the top, and processes at the bottom, with respect to article references, this hierarchy was reversed. This clear mismatch needs to be resolved in such a way that the interrelations between the different levels are by no

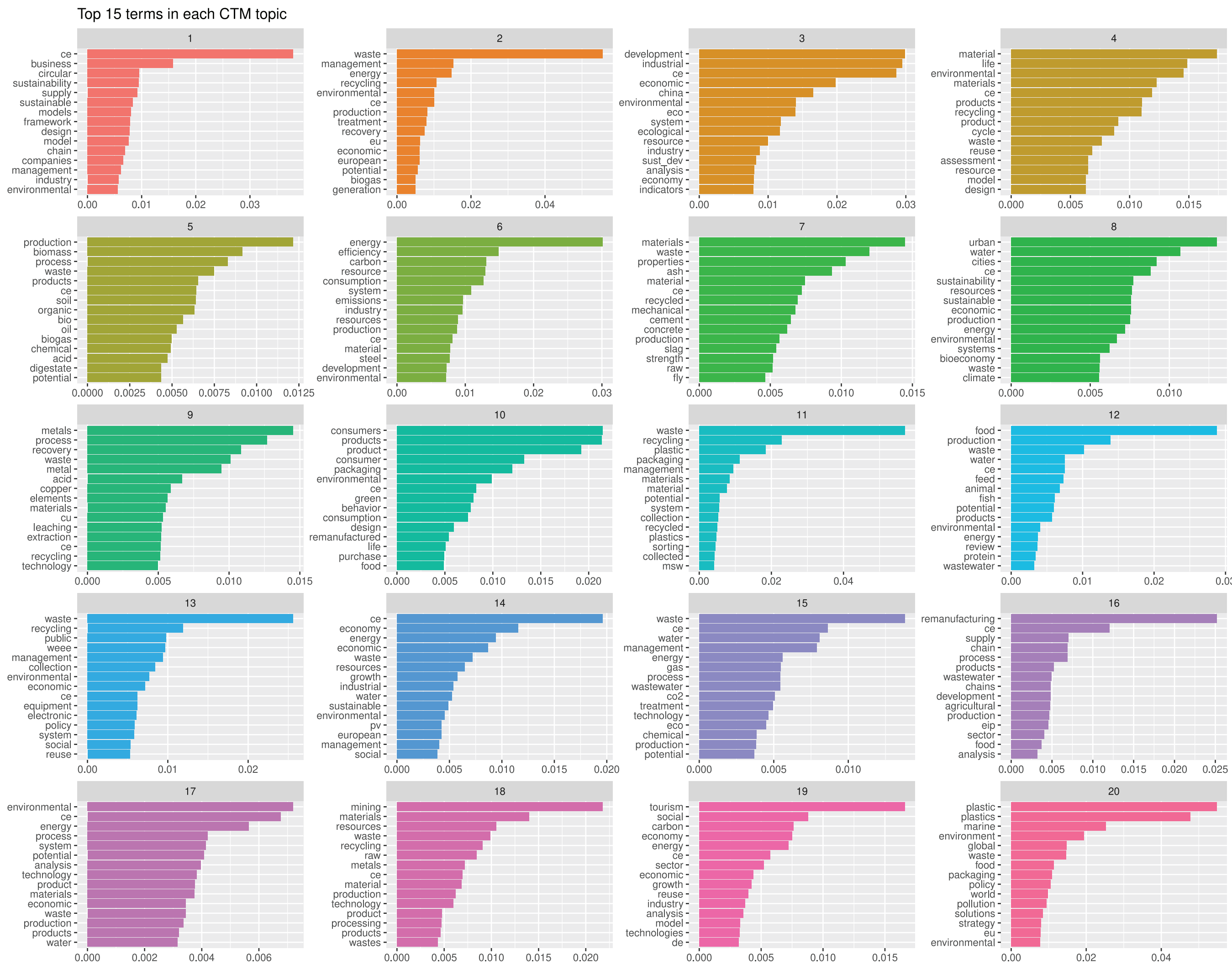

Fig. C2. Top 15 keywords per CTM topic.

means neglected (e.g. new DfX approaches on the material level are likely to influence company and marketing strategies, and hence the consumer), nor should any one level be overemphasized. A balance of research, accompanied by an effort to unify sustainability assessment is thus seen as being key to the successful contribution of CE research to the sustainability agenda.

6. Conclusion

The objective of this study was to shed light on the current state and evolution of CE research, in general, and its sustainability connotation, in particular. To do this, a mixed-methods approach was adopted, combining a longitudinal bibliographic network analysis, a multiple correspondence analysis, a correlated topic model, a historiographic citation analysis and a semantic content analysis. The results indicate that, in general, the CE body of literature can be divided into management and technically-oriented studies, and these have either a beginning-of-life (BOL) or an end-of-life (EOL) focus. Recycling is the most frequently referred to R-strategy, followed by remanufacturing, repair and reuse, although the frequency of the latter, is one order of magnitude lower. Regarding the connection to sustainability, previous qualitative research suggested the existence of a subset relationship between CE and SD, and this was in fact confirmed by the present study. The quantitative analyses showed that only a limited number of environmental aspects (such as waste, resource use and CO_2 emissions) are centrally addressed, while other environmental and social aspects form the periphery of CE research. In this context, material flow and life cycle analysis are the most frequently referred to methods of sustainability assessment, apart from specific circularity assessments that have been developed in recent years. It was also interesting to see that in the early phases of CE research, papers mainly assumed win-win-situations with respect to the requirements of environmental and economic sustainability. This has been increasingly challenged in the more recent years of CE research.

The CE mainstream, in both the BOL and EOL phase, is dominated by a corporate perspective, and the consumer's MOL perspective continues to receive only scant attention. While higher value retention options are tendentially closer to the consumer, the bibliometric analyses showed that only about 1% of CE-related papers were tagged with consumer-focused terms and that they did not form a specific research theme or cluster. Similarly, in the topic modeling only one out of 20 topics included the words consumers and consumption alongside product(s) and packaging. Consequently, from a quantitative perspective, the lack of consideration given specifically to consumption patterns and citizen inclusion is clearly a blind spot in the CE debate. Content analysis also revealed a strong need to vigorously reflect upon which tools or models might be needed to promote circular transitions and sustainability outcomes, and how potential barriers to an upscaling process may be dealt with.

Table C1
Summary of the interpretation of the Correlated Topic Model. Top 20 terms are ordered according to their contribution to the respective topic.

Topic	Gamma	Waste	R-Strategy	Sust. Dim. environmental	Economic	social	Top 20 terms
Topic 1	0.175				X		ce, business, circular, sustainability, supply, sustainable, models, framework, design, model, chain, companies, management, industry, environmental, practices, economic, innovation, implementation, resource
Topic 2	0.095	x	Recycling	x			waste, management, energy, recycling, environmental, ce, production, treatment, recovery, eu, economic, european, potential, biogas, generation, solid, analysis, system, countries, materials
Topic 3	0.087			x	X		development, industrial, ce, economic, china, environmental, eco, system, ecological, resource, industry, sust_dev, analysis, economy, indicators, model, symbiosis, policy, environment, resources
Topic 4	0.087	x	Recycling	x			material, life, environmental, materials, ce, products, recycling, product, cycle, waste, reuse, assessment, resource, model, design, impacts, production, impact, building, lca
Topic 5	0.068	x					production, biomass, process, waste, products, ce, soil, organic, bio, oil, biogas, chemical, acid, digestate, potential, treatment, anaerobic, food, mg, obtained
Topic 6	0.061				x		energy, efficiency, carbon, resource, consumption, system, emissions, industry, resources, production, ce, material, steel, development, environmental, economic, agricultural, analysis, reduction, emission
Topic 7	0.060	x					materials, waste, properties, ash, material, ce, recycled, mechanical, cement, concrete, production, slag, strength, raw, fly, products, thermal, environmental, steel, industrial
Topic 8	0.059				x		urban, water, cities, ce, sustainability, resources, sustainable, economic, production, energy, environmental, systems, bioeconomy, waste, climate, city, global, social, change, challenges
Topic 9	0.050	x					metals, process, recovery, waste, metal, acid, copper, elements, materials, cu, leaching, extraction, ce, recycling, technology, chemical, solution, zn, production, lithium
Topic 10	0.034			x			consumers, products, product, consumer, packaging, environmental, ce, green, behavior, consumption, design, remanufactured, life, purchase, food, model, services, impact, market, remanufacturing
Topic 11	0.031	x	Recycling				waste, recycling, plastic, packaging, management, materials, material, potential, system, collection, recycled, plastics, sorting, collected, msw, polymers, analysis, quality, energy, composition
Topic 12	0.031	x					food, production, waste, water, ce, feed, animal, fish, potential, products, environmental, energy, review, protein, wastewater, sustainable, industrial, quality, industry, system
Topic 13	0.030	x	Recycling	x	x		waste, recycling, public, weee, management, collection, environmental, economic, ce, equipment, electronic, policy, system, social, reuse, model, responsibility, common, companies, electrical
Topic 14	0.025	x			x		ce, economy, energy, economic, waste, resources, growth, industrial, water, sustainable, environmental, pv, european, management, social, environment, impact, global, systems, analysis
Topic 15	0.022	x		x			waste, ce, water, management, energy, gas, process, wastewater, co2, treatment, technology, eco, chemical, production, potential, innovation, model, system, adsorption, economic
Topic 16	0.020	x	Remanu-facturing				remanufacturing, ce, supply, chain, process, products, wastewater, chains, development, agricultural, production, eip, sector, food, analysis, loop, european, environmental, standard, automotive
Topic 17	0.019			x			environmental, ce, energy, process, system, potential, analysis, technology, product, materials, economic, waste, production, products, water, impact, bio, coffee, specific, sludge
Topic 18	0.018	x	Recycling				mining, materials, resources, waste, recycling, raw, metals, ce, material, production, technology, product, processing, products, wastes, mine, cmm, process, environmental, water
Topic 19	0.016		Reuse		x	x	tourism, social, carbon, economy, energy, ce, sector, economic, growth, reuse, industry, analysis, model, technologies, de, green, terms, global, production, development
Topic 20	0.012	x		x			plastic, plastics, marine, environment, global, waste, food, packaging, policy, world, pollution, solutions, strategy, eu, environmental, materials, material, issue, production, debris

Table D1
30 most influential papers in the circular economy and sustain* literature. (rel.) LCS = (relative) Local citation score; GCS = global citation Score; INC = Intra-network citations.

Paper	DOI	LCS	GCS	rel. LCS	INC
Zhijun, 2007, SUSTAINABILITY SCI	10.1007/S11625-006-0018-1	52	118	44.07%	8
Andersen, 2007, SUSTAIN SCI	10.1007/S11625-006-0013-6	100	168	59.52%	11
Geng, 2008, INT J SUSTAINABLE DEV WORLD ECOL	10.3843/SUSDEV.15.3:6	101	235	42.98%	11
Park, 2010, J CLEAN PROD	10.1016/J.JCLEPRO.2010.06.001	45	141	31.91%	4
Mathews, 2011, J IND ECOL	10.1111/J.1530-9290.2011.00332.X	71	175	40.57%	9
Geng, 2012, J CLEAN PROD	10.1016/J.JCLEPRO.2011.07.005	114	263	43.35%	9
Su, 2013, J CLEAN PROD	10.1016/J.JCLEPRO.2012.11.020	148	317	46.69%	6
Bakker, 2014, J CLEAN PROD	10.1016/J.JCLEPRO.2014.01.028	60	175	34.29%	8
Haas, 2015, J IND ECOL	10.1111/JIEC.12244	66	217	30.41%	5
Gregson, 2015, ECON SOC	10.1080/03085147.2015.1013353	62	136	45.59%	4
Ghisellini, 2016, J CLEAN PROD	10.1016/J.JCLEPRO.2015.09.007	306	784	39.03%	7
Bocken, 2016, J IND PROD ENG	10.1080/21681015.2016.1172124	131	310	42.26%	3
Lewandowski, 2016, SUSTAINABILITY	10.3390/SU8010043	100	208	48.08%	4
Sauv, 2016, ENVIRON DEV	10.1016/J.ENVDEV.2015.09.002	65	170	38.24%	5
Witjes, 2016, RESOUR CONSERV RECYCL	10.1016/J.RESCONREC.2016.04.015	52	148	35.14%	1
Moreno, 2016, SUSTAINABILITY	10.3390/SU8090937	43	89	48.31%	1
Lieder, 2016, J CLEAN PROD	10.1016/J.JCLEPRO.2015.12.042	170	327	51.99%	7
Geissdoerfer, 2017, J CLEAN PROD	10.1016/J.JCLEPRO.2016.12.048	259	581	44.58%	4
Kirchherr, 2017, RESOUR CONSERV RECYCL	10.1016/J.RESCONREC.2017.09.005	159	390	40.77%	2
Murray, 2017, J BUS ETHICS	10.1007/S10551-015-2693-2	155	326	47.55%	6
Genovese, 2017, OMEGA	10.1016/J.OMEGA.2015.05.015	93	215	43.26%	3
Pomponi, 2017, J CLEAN PROD	10.1016/J.JCLEPRO.2016.12.055	48	107	44.86%	1
Elia, 2017, J CLEAN PROD	10.1016/J.JCLEPRO.2016.10.196	42	97	43.30%	1
Urbinati, 2017, J CLEAN PROD	10.1016/J.JCLEPRO.2017.09.047	44	90	48.89%	1
LINDER M, 2017, BUS STRATEG ENVIRON	10.1002/BSE.1906	59	109	54.13%	3
Korhonen, 2018a, ECOL ECON	10.1016/J.ECOLECON.2017.06.041	102	242	42.15%	2
Kalmykova, 2018, RESOUR CONSERV RECYCL	10.1016/J.RESCONREC.2017.10.034	55	128	42.97%	0
Korhonen, 2018b, J CLEAN PROD	10.1016/J.JCLEPRO.2017.12.111	44	102	43.14%	0
Merli, 2018, J CLEAN PROD	10.1016/J.JCLEPRO.2017.12.112	43	94	45.74%	0
Prieto, 2018, J CLEAN PROD	10.1016/J.JCLEPRO.2017.12.224	44	91	48.35%	0

6.1. Further research

Based on the findings, the following suggestions can be made regarding further research. First, the CE-SD relation must be investigated in practice in order to uncover potential CE applications and how these may contribute to sustainable development. Second, the advancement and application of integrated sustainability and circularity assessment methods could be used to foster strategic decision-making from a sustainability perspective. Finally, the consumers' role in a CE needs to receive particular attention, as social considerations are essential in any move towards economic transformation. In this respect it appears vital to strive for an integration of (i) the material, (ii) the strategic, and (iii) the consumer perspectives. Only by combining those three perspectives adequately, can a systemic CE transition, one which is in line with the principles of sustainability, be successfully accomplished.

6.2. Limitations

To minimize the number of potential limitations, quantitative and qualitative methods were used in an integrated manner, and several measures, outlined in Section 3 above, were undertaken in order to maximize the data quality. Limitations may remain with regard to the decisions to be taken for the design of the quantitative analyses, such as the definition of the search strings, minimum frequencies in the thematic maps in Section 4.1, the minimum degree in the multiple correspondence analysis in Section 4.2 and the number of papers in the historiographic analysis in Section 4.4. These decisions were guided by the need to maintain the interpretability of the results. The review protocol summarising these decisions, as well as the data and code used is available at: https://osf.io/u2baw

Declaration of Competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

Acknowledgements

The financial support of the Austrian Federal Ministry for Digital and Economic Affairs, the National Foundation for Research, Technology and Development, and the Christian Doppler Research Association, is gratefully acknowledged.

Appendices

A - Thematic mapping
B - Conceptual structure
C - Correlated Topic Model
D - Historiographic analysis

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