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The Third Wave of LCA as the "Decade of Consolidation"

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Abstract: Several authors have pointed out the importance of systems thinking, and have considered both environmental and social aspects (holistic perspective) of sustainability assessment in the past. Sustainability assessment tools which integrate different aspects (e.g., environmental/social aspects) in order to identify negative impacts have already been developed. Common tools used to assess environmental, social, or economic impacts include the life cycle assessment (LCA), social life cycle assessment (S-LCA), life cycle costing (LCC) and life cycle sustainability assessment (LCSA) approaches. The goal of the present study was to investigate how and to what extent the three dimensions of sustainability (environmental, social, economic; holistic sustainability perspective) have been integrated into the field of LCA. A topic modeling method was applied to examine whether the emphasis placed on integrating environmental, social, and economic aspects in sustainability assessment has resulted in a more comprehensive application of the LCA approach. The results show that topics related to energy and infrastructure are currently prevailing, and that topics related to methods have been decreasing since 1997. A minor discussion of social aspects and a lack of discussion on economic aspects were identified in the present study. These results do not support the predicted "decade of life cycle sustainability assessment." Consequently, a new period of LCA extension and application is predicted, namely, the third wave of LCA as the "decade of consolidation." During this period, the LCA framework will be enhanced to reduce existing practical and methodological difficulties and integrate environmental and social aspects in a sustainability assessment to support global sustainable development.

Keywords: life cycle assessment; holistic sustainability; text mining; topic modeling; decade of consolidation

1. Introduction

Humanity faces several challenges while striving for sustainable development to create stable social systems within ecological limits. Critical processes related to the Earth sciences can destabilize such systems, as has been shown with the planetary boundaries approach (PBA). Steffen et al. [1] showed that four out of nine planetary boundaries have already been crossed (namely, the biosphere integrity, climate change, biogeochemical cycles, and land-system change boundaries). Problems deriving from crossing these boundaries have arisen on a global scale, and decision-makers have to direct their activities to address these sustainability challenges to operate "in a safe space" [2]. Business activities strongly impact the environment and society; these impacts can be quite diverse, requiring specific management instruments [3]. Thus, businesses are increasingly being confronted with questions regarding how to increase their environmental and social performance levels. A deeper understanding of how to tackle these sustainability challenges is needed, and "simple-to-use" (but not necessarily simplistic!) methods which provide reliable results that can serve as platforms for decisions at different levels of the society [4] are demanded. One relevant tool that can be used to assess the environmental sustainability of products or services is life cycle assessment (LCA). An LCA is a flexible tool, as it allows researchers to perform an assessment not just of existing products or services but also at a very early stage of development [5] or on different levels of products, sectors, and economies [6]. So far, LCA has become a widely acknowledged tool and its use is encouraged by governments all over the world (e.g., USA, Japan, Canada, European Union, India, and China) [6]. However, LCA is not only interesting because it is widely known and adopted, but also because it is one of the best developed and most frequently used environmental sustainability assessment tools [7]. McManus and Taylor [8], for instance, identified about 11,700 publications that mentioned LCA for their review on the development of LCA, focusing on qualitative text analysis. Finnveden et al. [9] and Guinnée et al. [6] cite that LCA and the interest in LCA grew rapidly in the 1990s.

The discussion on integrating social aspects into LCA started in the 1990s [10–13], and this discussion deepened remarkably from 2003 to 2006 [4,12–14]. However, few studies were reported in the literature on social life cycle assessments (S-LCAs), and a consolidation of a holistic perspective of LCA, including life cycle costing (LCC) and S-LCA, is needed [15–17].

Given the importance of LCA and the arguments to integrate social and economic aspects, a systematic analysis can consolidate our understanding of the scientific discourse on LCA. Hence, three research questions (RQs) were addressed in this paper:

(RQ1) How has the LCA literature developed?
(RQ2) What main topics have been covered in the literature on LCA?
(RQ3) Which sustainability topics have been covered in the literature on LCA?

In the present paper, a primary focus is placed on describing the recent development in the literature on LCA and the consistency of topics related to LCA. The results of this examination allowed us to conclude whether the developments in LCA, as viewed from a holistic sustainability perspective, can be defined as being in the "decade of life cycle sustainability assessment (LCSA)" as proposed by Guinée et al. [6]. The results of the literature analysis provide important insights into which further research is needed to optimize LCA.

In the next section, the theoretical background is presented, and a focus is placed on topics such as LCA, the ISO 14040/44 standards, and the importance of taking a holistic view of sustainability and LC(S)A. The topic modeling research method applied in this research is explained in the Methods section, which is followed by the main Results and Discussion sections. Finally, conclusions are drawn to highlight important outcomes and give insights into future research needs regarding a third wave of LCA research.

2. Theoretical Background

The following discussion provides a theoretical background of LCA in general, and also describes its historical development. As part of the historical examination of LCA, a more comprehensive perspective is achieved by integrating the three dimensions of sustainability (environmental, social and economic perspectives, LCSA) in LCAs, as shown in Section 2.2. However, it is necessary to broaden the scope of LCAs or LCSAs, as was highlighted by Onat et al. [18], who argue that "current applications of LCSA have not considered rebound effects, feedback mechanisms, and interrelations of the system of interest sufficiently." They explain that a rebound effect could occur as a result of any feedback from the system-of-interest, economy, and environment, or interconnections with, for example, indirect effects, dynamic relationships among social, economic, and environmental dimensions, or market mechanisms [18]. Including such rebound effects, feedback mechanisms and interrelations can broaden and improve the scope of LCAs or LCSAs.

2.1. Life Cycle Assessment

Various methods and tools can be used to assess the sustainability impacts of products, services, or predefined systems [7]. According to Ness et al. [7], these tools can be categorized according to their temporal foci (retrospective or prospective). Retrospective tools include indicators or indices, and prospective tools include integrated assessments. Product-related assessment tools can be both retrospective and prospective. LCA is considered to be a product-related assessment method, and is a widely acknowledged tool that can effectively be used to assess the life cycle impacts of a product [6,9].

The first attempts to compare the environmental impacts of consumer products were made in the late 1960s [6,8]. LCA was further developed in the early 1990s in a workshop held by the Society of Environmental Toxicology and Chemistry (SETAC) [19]. The outcome of this workshop was a guideline, which in the late 1990s was amended to meet ISO standards [8,20]. The standards were most recently revised in 2006 [21,22]. According to ISO 14040: 2006 [21], a life cycle assessment can be used to assess the environmental impacts of a product system along its life cycle (e.g., from the stage of raw material extraction to the end-of-life of a product) [9,21]. Since the first attempts to use the tool were made in the late 1960s, it has gained in popularity and been used in many contexts, such as to assess waste management systems, building materials, or tourism [6]. However, Guinée et al. [6] state that the ISO standards were never applied to standardize the LCA in detail, despite the increase in the popularity of its use and the scope of its applications. This resulted in some creative leeway regarding how to interpret some of the ISO requirements and diverging approaches being taken in the development of the LCA [6]. Finnveden et al. [9], for instance, differentiate between performing attributional or consequential LCA as well as input–output or hybrid LCA. Moreover, differences in setting the system boundaries and how to spatially differentiate the impacts [9,23] were identified.

ISO [21] states that LCA "typically does not address the economic or social aspects of a product." The methodology of LCA is still being discussed; for example, Finnveden et al. mentioned in 2009 that LCA was still under development [9]. Even more recent publications like Weidema et al. [23], who discussed attributional and consequential LCA, show that the development of the method is still ongoing. This shows that the LCA is a popular environmental sustainability assessment tool that is frequently used, but the scope of conducted LCAs might still be too narrow (e.g., Onat et al. [18]).

2.2. Holistic Perspective of LCAs

Ny et al. [24] argue that "LCAs often lack a sustainability perspective and bring about difficult trade-offs between specificity and depth on the one hand, and comprehension and applicability on the other." These authors claim that an assessment needs to integrate numerous and complex social, ecological, and economic factors. Therefore, as LCAs are often used, they are not applied broadly enough. Several authors of scientific papers have suggested that this broader and holistic perspective in sustainability is essential for a movement towards global sustainable development [25–32]. Principles were already established to initiate such a movement in 1996 in a meeting in Bellagio [33]. One of these Bellagio Principles highlights the importance of holistic sustainability [34,35]. A holistic form of sustainability describes a multidimensional approach, in that it places a focus on environmental, social, and economic performance, and positions it at the core of any corporate activity [31]. In a holistic approach, the world has to be viewed as a single, interconnected, enormous system, requiring system-level thinking. Businesses and business activities are part of this system, so business leaders have to develop their sustainability strategies while considering both positive and negative impacts on the whole system. This aspect was emphasized by Gianni et al. [28], who argue that sustainability initially has to be "managed within a system" and then "the performance of this sustainability management needs to be managed and measured." A system perspective or a more comprehensive sustainability perspective has been emphasized in the literature on LCA in the past (see Figure 1) [18]; however, the inclusion of this sustainability perspective has infrequently been observed [15–17].

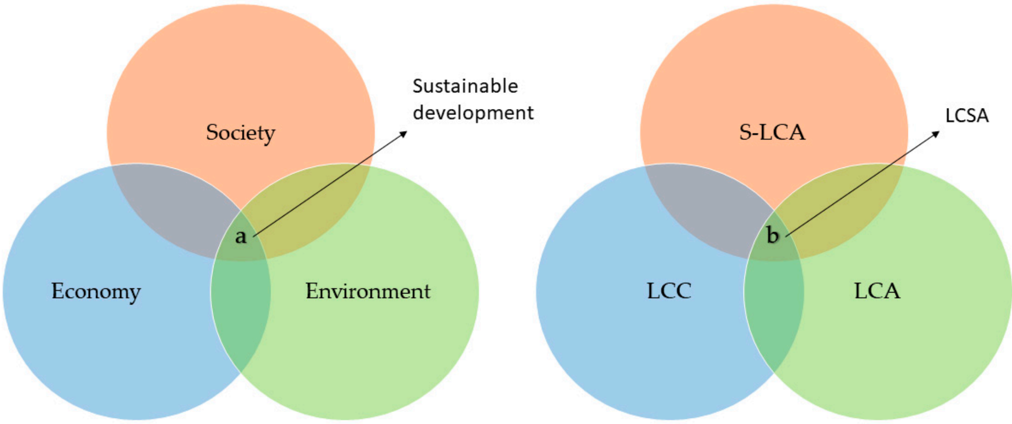

Figure 1. Holistic sustainability perspective (economy, environment, and society) of (**a**) sustainable development and (**b**) life cycle sustainability assessment (LCSA) based on reference [36]. LCA: life cycle assessment; LCC: life cycle costing; S-LCA: social life cycle assessment.

The LCA approach is mentioned as a suitable tool, but Robèrt [37] states that an LCA is not being used in a "comprehensive enough" way, and is not the best tool for strategic decisions. In 2006, Ny et al. [23] emphasize this point again when they integrate the principles of sustainability of the Framework for Strategic Sustainable Development (FSSD) into strategic life-cycle management (SLCM). They compared streamlined, traditional, and strategic LCA and argued that instead of narrowing the scope (e.g., in streamlined LCAs), a systems view needed to be taken [24]. The focus and emphasis placed on this aspect for more than ten years has suggested that the LCA has changed, gaining a more comprehensive view and scope and integrating ecological, social, and economic aspects. This period of change is referred to by Guinée et al. [6] as the "decade of LCSA" (2010–2020), a period of time during which the method itself will be improved and completed and during which a complete sustainability perspective will be integrated. Although the discussion on LCSA was initiated during this decade, and the first case studies on LCSA appeared, the latest papers and reviews have shown that methodological challenges still exist, and a holistic perspective in LCAs is still missing. In 2015, Mc Manus and Taylor concluded that the "methods and data have not caught up with demand" [8]. In 2017, Onat et al. mentioned that one limitation of the LCAs is that they can only be used to evaluate impacts in isolated ways [18]. One year later in 2018, Sureau et al. argued that although E-LCA (environmental LCA) and LCC are consolidated, S-LCA is still not optimized. The method "still faces a number of methodological challenges, like to match the method to the life-cycle thinking framework (e.g., the link with the functional unit), the setting of system boundaries, the definition and selection of assessment criteria and indicators, and defining impact assessment methods" [38].

Nonetheless, frameworks and guidelines that can be used to assess social and economic impacts within LCA are currently available [14,39,40], while the earlier versions of the LCA could only be used to measure environmental impacts [6]. An S-LCA is defined as an assessment of social impacts (and potential impacts) on several stakeholders along the life cycle of products and especially workers, consumers, local communities, members of society, and other value-chain actors who are affected by the production and consumption of products [41]. The consideration of social and socio-economic impacts was first discussed in the SETAC Workshop Report [10]. The frameworks and guidelines have been further developed, and researchers attempted to find and evolve (qualitative and quantitative) frameworks and methodologies for S-LCAs. Several quantification methodologies for S-LCA are currently available, such as that of Fan et al. [42], who reviewed the four S-LCA methodologies proposed by Dreyer et al. [14], Hunkeler [12], Norris [13], and Weidema [40]. The framework of Dreyer et al. [14] includes aspects of the ISO standard for environmental LCAs, and this framework is the first complete concept of S-LCA [42]. This framework is an initial attempt to measure social impacts directly on people rather than taking a unit process perspective [14,42]. Unlike Dreyer et al. [14], Hunkeler [12] calculated labor hours with existing data from environmental LCAs on unit processes. Norris [13] used the subcategory "health impact" as an example and developed an endpoint approach, which means that cause–effect relations were shown. The framework of Weidema [40] is an approach based on assessed damage, using the indicator quality-adjusted life years (QALYs) as the basis. Jørgensen et al. [43] also provide an overview on the developments in S-LCA methodologies. To measure economic impacts, the LCC approach, which is also known as life cycle costing or total cost of ownership, can be used to assess the relevant costs associated with a product's whole life cycle [44]. The LCC originated in the mid-1960s, when it was first used by the United States Department of Defense [45].

An assessment that includes environmental, social, and economic aspects within an LCA is also referred to as an LCSA [6,27,36,46,47]. In general, an LCSA is a combination of various tools, namely, LCA, LCC, and S-LCA [6,46]. As already illustrated in Figure 1, this LCSA integrates the holistic perspective of sustainability, which is known as the three dimensions of sustainable development as described by Lozano (2008) [32]. The environmental LCA, which is also the only standardized LCA approach, has now been practiced for more than 40 years [36], but the LCC and S-LCA are still under development [15,48,49]. This makes a holistic assessment such as an LCSA even more challenging, and demands much more and deeper research to develop methodology and carry out case studies to develop and test these frameworks and tools.

3. Methods

To investigate the inclusion of the three dimensions of sustainability, a large-scale analysis of the LCA literature was required. Such an analysis is an endeavor that is not appropriate without a suitable literature database or computational analysis method, both of which were influencing factors of central importance in this study.

In terms of a literature database, the Scopus abstract and citation database was chosen, as it covers most of the social science journals, and about four out of five natural science journals [50]; LCAs and related topics are described in these two research fields. Moreover, Scopus only lists peer-reviewed publications. The Scopus database was queried to identify literature on LCA with the keywords "life cycle assessment", "life cycle analysis", "iso 14040" and "iso 14044". By choosing "article" as the only document type, we intentionally excluded reviews, conference papers, and other types of publications to prevent ourselves from obtaining duplicate information about research projects. The query was performed on 20 January 2018 and yielded information on 15,302 peer-reviewed publications. As it was not feasible to gather so many publications, and due to access restrictions, only abstracts were collected in the present study. We assumed that the abstracts outline the content of papers and, therefore address the subjects under discussion (cf. [51]), and concluded that the collected corpus of abstracts provided a suitable dataset for analysis.

The knowledge discovery method of topic modeling [52] was applied as an analytical method. Topic modeling is a computational method based upon a statistical modeling process that allows researchers to automatically screen a textual corpus and draw conclusions about the topics under discussion. Topic modeling is based theoretically on the assumption that topics in texts are represented by nouns, whereas other parts of speech such as verbs, adjectives, and other parts of speech do not play roles as topics [53]. Topic modeling is used to analyze the prevalence and co-occurrence of all nouns in a textual corpus in order to establish an overview of the topics under discussion. Since each noun in the textual corpus is analyzed automatically with the modeling algorithm, no manual preselection of nouns is required. The modeling process results in the collection of clusters of nouns that represent topics in the corpus. Within each cluster, the nouns are ranked by their prevalence, which is also determined during the modeling process. The most prevalent nouns of a cluster can then be used to label that cluster, and such a labelled cluster is understood as a topic.

From a technical perspective, researchers do not need prior knowledge about the corpus under investigation to apply the topic modeling method. However, researchers must have background knowledge about the corpus in order to interpret the modeling results. The only mandatory input parameter for topic modeling is the number of topics that will be modeled. So, it is possible to model only a few topics in a textual corpus or several hundred topics in the same corpus. However, modeling a low number of topics leads to poor resolution of results and, hence, to broad topics, which allows the researcher to generate a broad picture of the corpus under investigation but does not reveal fine details. On the contrary, modeling a large number of topics allows researchers to conduct an in-depth analysis of a corpus, but does not allow them to generate a broad and comprehensible picture. Therefore, researchers need to decide how many topics to model in a textual corpus before they apply the topic modeling method, carefully considering the research question.

Following the approach of [54], the topic modeling method was applied nine times for this survey, and each time for a different predefined number of topics. This made it possible to determine the number of topics that would allow us to gain a broad picture on the one hand, but still uncover details of the corpus on the other. Hence, the modeling was performed for 5, 10, 15, 20, 25, 30, 40, 50, and 100 topics. These nine models yielded nine different results, which were then compared. During this process, the model considering 20 topics turned out to be suitable for this survey, as this number provided the best trade-off between depth of focus and number of topics.

The actual process of topic modeling required several steps of data processing, as knowledge discovery methods typically do [55]. For each of the 15,302 abstracts, the model was used to extract the nouns, trace the nouns to their linguistic roots, and subsequently count these root nouns. The step of stemming the extracted nouns to the root nouns has been observed to improve the results in topic modeling [52]. Counting these root nouns in a so-called term–document matrix (see Table 1) laid the foundation for the final modeling step. In total, the term–document matrix consisted of 6445 rows (each row related to one root noun) and 15,302 columns (each column related to one article abstract).

Table 1. Excerpt from the term-document matrix. The rows refer to root nouns of extracted nouns ("terms"), and the columns refer to abstracts ("documents"), which are identified here by abbreviated article titles. For this excerpt, five abstracts of publications about life cycle assessment (LCA) were chosen arbitrarily. The excerpt lists terms that occurred in at least three out of the five selected abstracts.

	Deficit Irrigation with Reclaimed Water in A Citrus Orchard . . .	**Possibilities of Using the Tourism Area Life Cycle Model . . .**	**Techno-Economic and Environmental Assessment of . . .**	**Sizing of A Standalone Photovoltaic Water Pumping System . . .**	**Techno-Economical Analysis Based on A Parametric . . .**
climat	-	1	1	-	3
convers	1	-	2	-	1
cost	-	-	1	1	2
cycle	-	2	-	1	2
energi	7	-	-	2	15
perform	-	-	1	3	3
product	2	-	3	-	2
studi	3	-	1	-	1

The term–document matrix provided the input for the central step of the topic modeling method, which was performed using the open-source library software Genism [52]. This central modeling step allowed us to identify repetitive patterns of noun co-occurrences in the term–document matrix. These patterns were then reflected as clusters of nouns, topics that frequently co-occurred in the abstracts under investigation. These data processing and modeling steps generated twenty clusters of frequently co-occurring nouns, which could be interpreted as topics. The interpretation of these clusters—each of which represented a research topic in the LCA literature—was performed manually by the authors of this study by reading, interpreting, and discussing the text meanings. As part of this process, each of the established clusters (=topics) was labeled manually by referring to nouns that frequently occurred in the labelled cluster and by considering common LCA narratives that seemed similar to the nouns in that topic.

4. Results

We observed an increase in the relative share of papers on LCA in the 1990s (relative share = papers on LCA per year compared to the total number of publications per year) by examining the query results from the Scopus database (first wave of LCA); however, we also observed a steeper incline after 2006 (second wave of LCA) (Figure 2).

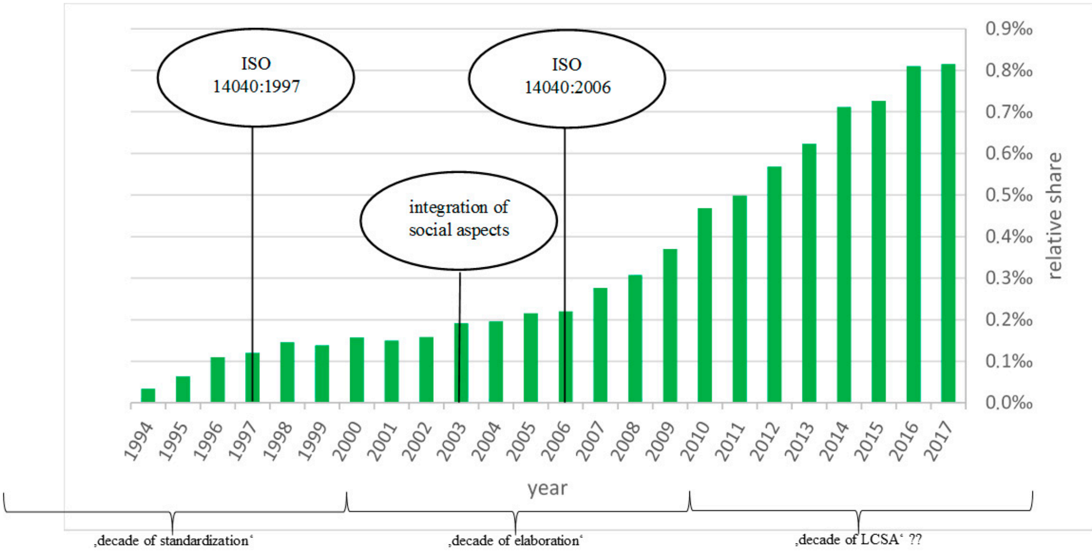

Figure 2. Temporal development of papers on LCA identified by querying the Scopus database (papers published from 1994 to 2017) in relative numbers (papers on LCA per year/total number of publications per year). The publications that appeared in 2018 were part of this study as well, but their share was not included in this figure, as the data would distort the curve progression. The decades listed at the bottom of the figure were described by Guinée et al. [6].

Figure 3 shows the relative development of the literature on LCA, LCC, S-LCA, and LCSA. It indicates the early discussion of LCC (dash-dotted blue curve) in the scientific literature. An increase in the number of papers on LCC and LCA occurred in the 1990s, whereby the number of those on LCA (dotted green curve) increased steadily after 2005/2006. At the same time, some papers related to S-LCA appeared (small dashed red curve between 2005 and 2010). As the S-LCA curve shows, the number of papers related to S-LCA have increased since 2010. The curve of the life cycle sustainability assessment shows that some literature emerged around 2005 and that an increase of LCSA literature was observed after 2010. As the right axis of the Figure 3 shows, the proportion of the publications in Scopus on S-LCA, LCC, and LSCA is very low.

In the present study, 20 topics (clusters of frequently co-occurring nouns, see Appendix A) were identified as prevalent within the scientific literature on LCA. These manually labelled topics seem to be the most important topics covered in the literature. Figure 4 illustrates the share of each of these topics in decreasing order. The share represents the topic's relative proportion within the literature on LCA; therefore, this proportion reveals the strength of each topic within the body of literature. For example, the topic "agricultural systems" has a share of about 4%, which is twice as much as that of the topic "refinery systems," with a 2% share. The three strongest topics include two topics which are strongly associated with LCA methodology and its general application, and which were consequently labelled as "sustainability related application" and "product and process related application." These were labelled as methodic topics, as no specific topic was identified within these clouds, and they included root nouns that indicated methodic topics, such as "*framework*," "*applic*," "*inventori*," and "*methodolog*." The fifth-ranked topic was that of the impact categories of an LCA and the eighth-ranked topic was LCA modeling. The topics related to the LCA approach (methodology and general application) are highlighted in red in Figure 4. The nouns covered in each topic can be found in Appendix A. As the other topics show, several specific topics, such as the topic "energy systems," were ranked as the third-strongest topic, followed by "infrastructure," "transport systems," "waste systems," and "construction systems." The topics which dealt with the specific application of LCA ("sustainability related application" and "product- and process-related application") as a method to assess the environmental dimension are red-striped in Figure 4. The naming of all topics emphasizes the fact that the social and economic perspectives are highly undermined. Only one topic could be identified as a clearly anthropomorphic one (orange in Figure 4). This anthropomorphic topic, which was ranked 17th, was named using the umbrella term "population." Some examples of root nouns for the anthropomorphic topic are "*popul*," "*age*," "*fate*," "*health*," "*surviv*," "*mortal*," and "*diseas*." Furthermore, anthropomorphic nouns were identified as part of the topic "life cycle impact assessment," which includes "health." No noun in the 20 topic clusters (600 nouns in total) had a direct social context, e.g., "*soc*", "*socia*l" or a similar term. No noun indicated an economic context when the economic dimension was examined.

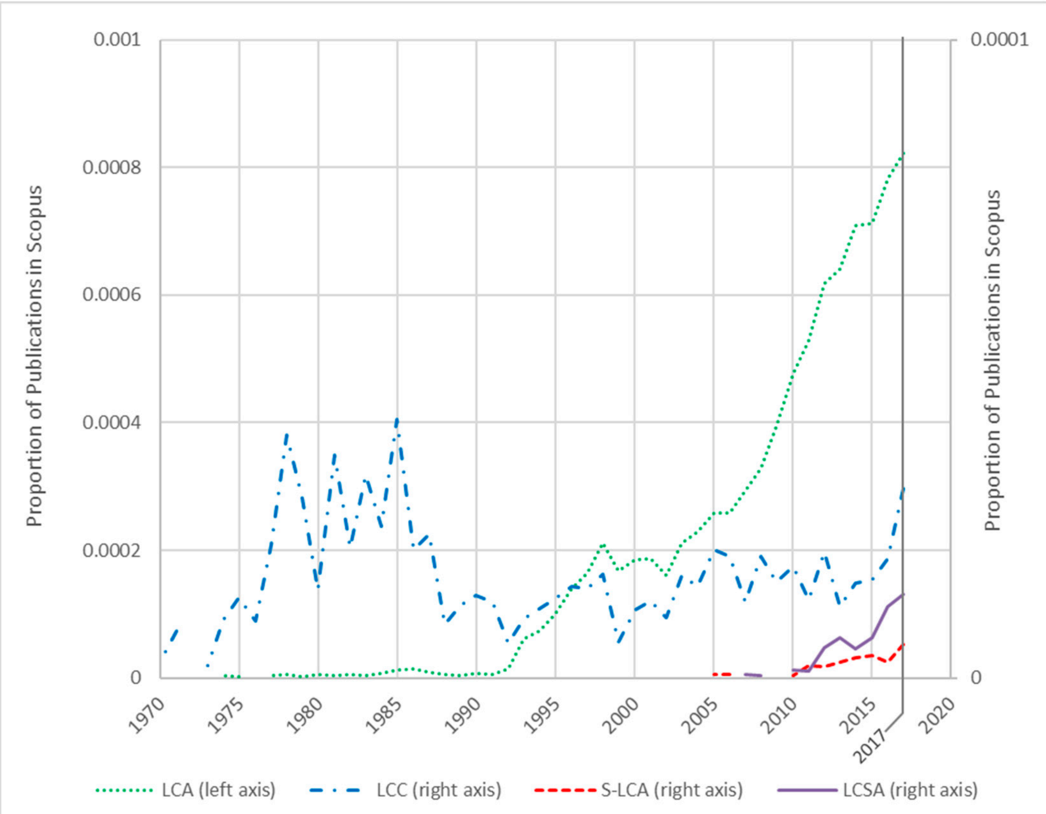

Figure 3. Relative temporal development of papers on LCA, LCC, S-LCA, or LCSA identified by querying the Scopus database (papers published from 1970 to 2017) and comparing their development to that of all publications identified using the database. Query criteria: literature on LCA was separated into papers on "pure" LCA (TITLE-ABS-KEY("life cycle assessment" OR "life cycle analysis" AND NOT ("social" OR "costing"))), LCC (TITLE-ABS-KEY("life cycle costing" AND NOT ("environmental" OR "social"))), S-LCA (TITLE-ABS-KEY("social lca" OR "social life cycle assessment" AND NOT ("environmental" or "costing"))) and LCSA (TITLE-ABS-KEY("life cycle sustainability assessment")).

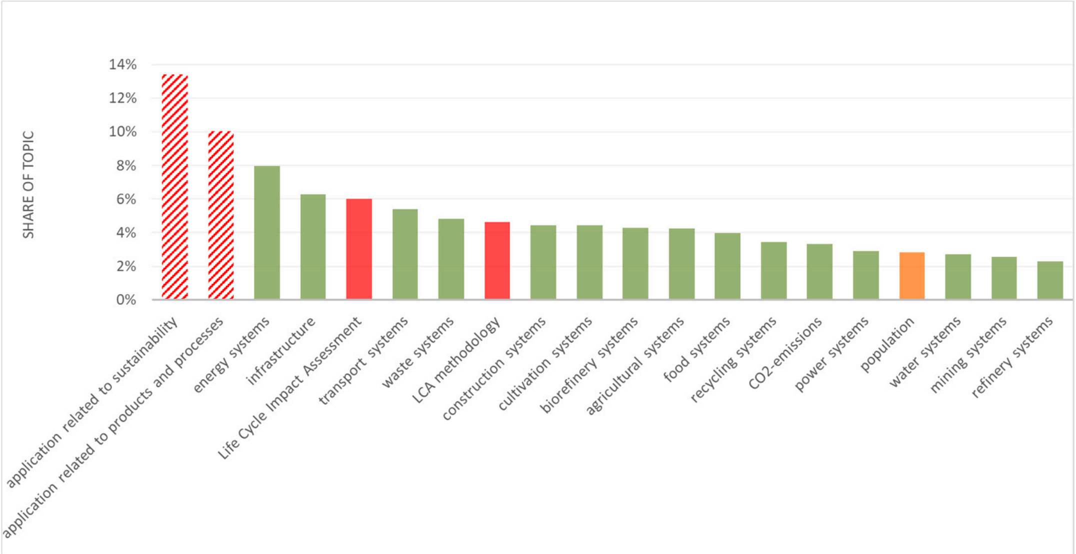

Figure 4. The share of 20 topics in the literature on LCA according to the findings of topic modeling. (red-striped = specific application of LCA; red = methodology of LCA; green = environmental topics; orange = social topic).

One aim of the present study was to identify the temporal dynamic of sustainability topics in the literature on LCA. The corresponding results are illustrated in Figures 5 and 6. In these figures, the graphs of the selected topics and their noteworthy temporal development are plotted. Each graph shows the temporal development with a moving average over a three-year period.

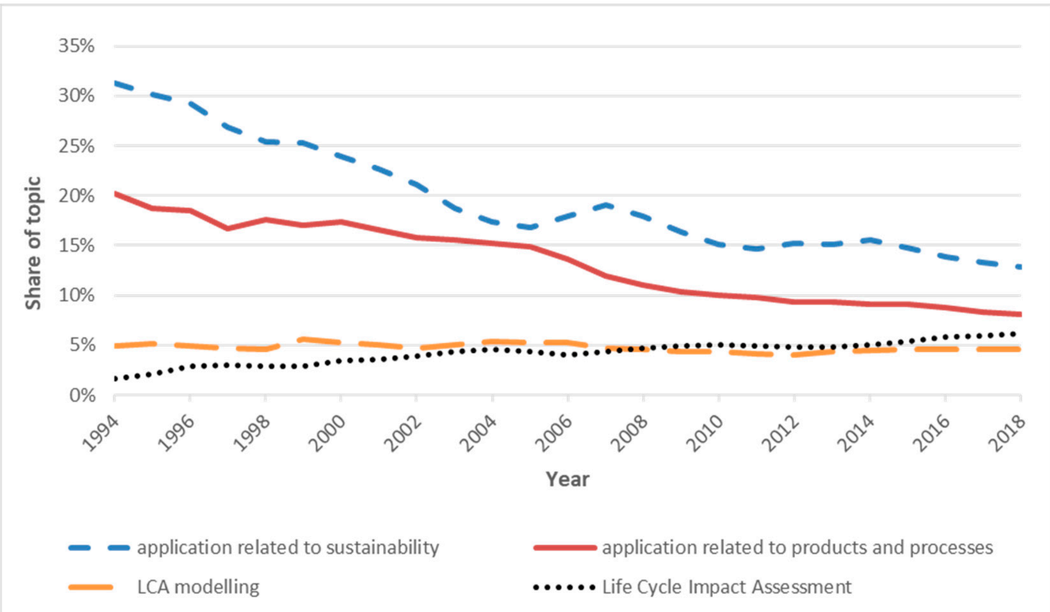

Figure 5. Temporal development of topics, focusing on method-related issues (moving average over a three-year period).

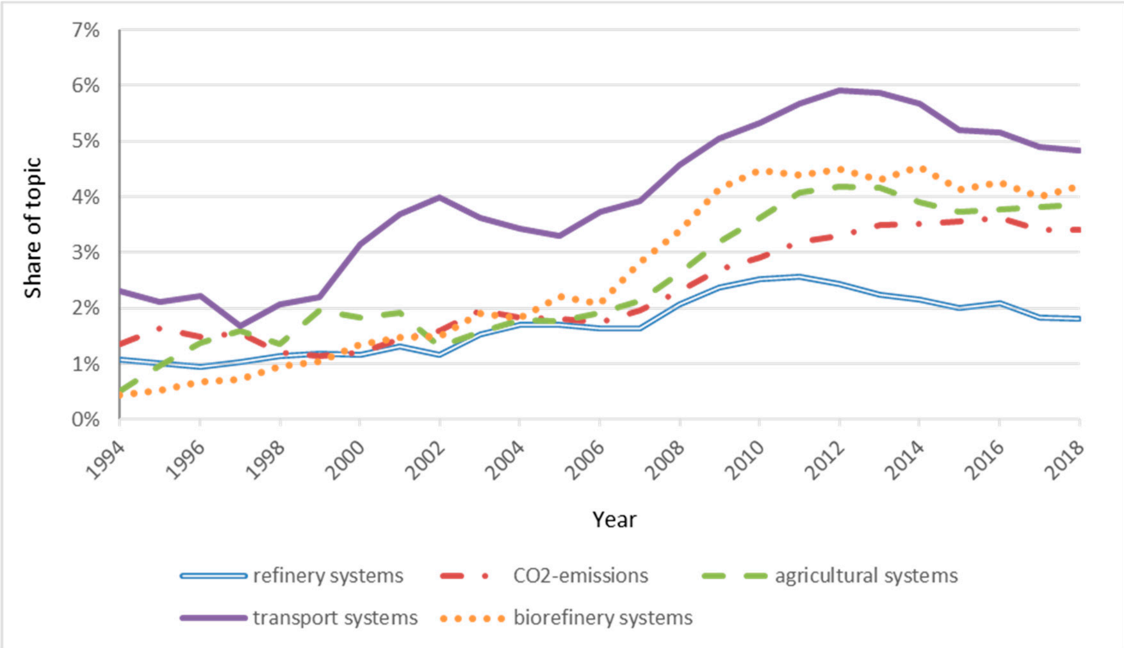

Figure 6. Temporal development of the topics related to refineries, CO_2 emissions, agriculture, transport, and biorefinery issues. These five topics show a correlation in their temporal development to some extent (moving average over a three-year period).

The share of the two strongest topics ("application related to sustainability" and "application related to products and processes") has decreased over the last 25 years. This means that the shares of these topics have decreased compared to those of other modeled topics. Figure 5 illustrates each topic that is related to the methodological details used in the LCA approach; two topics from a methodological perspective ("application related to sustainability" and "application related to products and processes"), one topic from a modeling perspective ("LCA modeling"), and one associated with impact assessment ("life cycle impact assessment"). The strongest root nouns in the modeling topic were "*model*," "*uncertainti*," "*variabl*," and "*sensit*," and the strongest nouns in the "life cycle impact assessment" topic were "*impact*," "*categori*," and "*lcia*." Some indications to impact categories were also noted (e.g., "*acidif*," "*eutroph*," and "*gwp*"). Figures 5 and 6 show topics that reveal a correlation in their temporal development to some extent, particularly after about 2006.

Another relation was observed among the topics with the umbrella terms "refinery systems," "CO_2 emissions," "agricultural systems," "transport systems," and "biorefinery systems." These five topics each had minor shares within the literature on LCA in the 1990s, but the importance of each of these topics increased slightly over time. The share of the topic "transport systems" peaked first in 2001/2002. From 2006 onward, the importance of these topics increased more rapidly and reached a maximum between 2011 and 2015.

5. Discussion

The goal of this research was to investigate the development of particular topics within the literature on LCA and determine whether and to what extent a holistic sustainability perspective was reflected in the LCA field. More than 15,000 abstracts that included topics related to LCA were analyzed using the topic modeling method to answer the research questions.

5.1. Developments within the Literature on LCA

Over the past few decades, the relative share of papers on LCA within the overall body of scientific literature has increased steadily, especially since 2007. The development of the ISO standards increased the acceptance of LCAs and has been interpreted as an important step towards a consolidation of the LCA methodology [56]. The observations in the present study (see Figure 2) are in accordance with the classification of "decades of LCA" [6]. Guinnée et al. [6] split the temporal development of LCA into four decades: 1970–1990 as the "decades of conception," 1990–2000 as the "decade of standardization," 2000–2010 as the "decade of elaboration," and as a prognosis, 2010–2020 as the "decade of life cycle sustainability assessment" (LCSA). Since 2010, the view on LCAs has broadened from a purely environmental perspective to include a holistic perspective of sustainability that includes environmental, social, and economic aspects (i.e., the LCSA).

However, because these LCAs did not provide a holistic sustainability perspective, more studies and papers were published on how to include social aspects in LCAs [4,12,14,39,42,43,46,57–61] or how to include all three dimensions of sustainability (LCSA) [16–18,36,46,47,62]. Although the number of studies and papers related to LCAs increased after 1994, it is still unclear as to whether the holistic sustainability perspective has been included more frequently (see Figure 2).

5.2. Topics in the Literature on LCA

The analysis allowed us to identify 20 central topics in the scientific literature on LCA, which were then manually labelled. Four general and methodological LCA topics were identified (i.e., "application related to sustainability," "application related to products and processes," "LCA modeling," and "life cycle impact assessment"). Fifteen topics related more closely to environmental topics were identified (e.g., "energy systems," "infrastructure," "transport," "waste," "construction and cultivation systems"), and only one topic was identified as a social topic (i.e., "population"). None of the topics were identified as an economic topic. These findings indicate that it could be difficult to determine whether and to what extent social and economic topics are covered in the literature on LCA, as even more environmental topics can be related to social topics as well. For example, the topic "food systems" can be a social topic, as "food systems" may relate to food insecurity, food allocation, or food availability. Waste and human health are also topics that were addressed frequently in former studies (Ahluwalia and Nema [63], Forastiere et al. [64], Heimersson et al. [65], Porta et al. [66]). Porta et al. [66] and Forastiere et al. [64] studied the possible health impacts of landfills and incineration plants. The two main impacts related to health identified were cancer incidence and adverse reproductive outcomes [66]. Furthermore, Heimersson et al. [65] mention that "resource recovery" from sewage sludge has the potential to save natural resources, but potential risks associated with human exposure to heavy metals, organic micro-pollutants, and pathogenic microorganisms worry stakeholders. They suggest that LCA is a suitable tool for assessing human health impacts and included pathogen risks to human health in their LCA [65]. These are just some examples of studies that included waste (management) and social topics in the literature on LCA. However, with respect to the topic modeling method applied, social topics were rarely (with one exception) identified as dominant topics, but they could be integrated in dominant environmental topics. However, no economic topic was identified as a dominant topic. The share of topics addressing social and economic aspects within the literature on LCA still seems to be minor. For this reason, we were not able to confirm that the "decade of LCSA" as proposed by Guinée et al. [6] has begun using the topic modeling method.

5.3. Temporal Development of the Literature on LCA

The results of applying the topic modeling method provided us with insights on the main topics covered in the literature on LCA. The higher share of environmental LCAs identified can be explained by the fact that LCA was developed as an environmental assessment tool. The environmental LCA is also the only standardized LCA approach available [21,22]; hence, it was frequently used in (case) studies. This increase in the share of environmental LCAs is shown in Figure 3; the first increase in the share (first wave of LCA) occurred between 1990 and 2000 (first ISO standard 1997) and the second steeper increase in the share (second wave of LCA) occurred between 2000 and 2010 (revised ISO standard 2006, discussion on integration social aspects and on LCSA). Figure 3 additionally illustrates the trends of LCC and S-LCA, whereby publications on LCC already existed before the 1990s, and publications on S-LCA started to appear after 2005. The discussion on integrating social aspects deepened after 2010. The curve development observed in this study matches the development trends seen in the existing literature. Neugebauer et al. [45] mention that LCC approaches had already been introduced in the 1960s, and the discussion of S-LCA was initiated in 2006 [12,14,40] and deepened after 2010. The number of case studies identified in the present study reflects these trends. An increase in the number of publications on LCA for all three dimensions was seen around the year 2010, which can be explained by the fact that papers on LCSA emerged, a method that integrates the three dimensions of sustainable development (e.g., Klöpffer [46], Finkbeiner et al. [62], and Schau et al. [36]).

The temporal development of the topics observed shows that the share of methodological topics ("application related to sustainability" and "application related to products and processes") decreased after 1994 (Figure 5). This can be explained by the fact that publications on method development generally emerge shortly after a new methodology is introduced. The share of publications on methods then usually decreases after the topic has been extensively discussed, and publications on the use and testing of the method increase in importance. In the present study, we argue that the change from one wave to another wave occurred when a topic had been sufficiently and thoroughly discussed. An indicator for this timepoint could be identified as the point when the literature reviews appeared (the first literature reviews on LCA appeared in the 2000s) and the point at which the number of case studies increased abruptly (as observed in the present study as increases in the shares of respective topics).

The shares of two methodological topics did not decrease, but instead slightly increased within the chosen time frame, namely, "LCA modeling" and "life cycle impact assessment." This finding can be explained by examining the problems discussed in literature reviews; challenges still exist concerning, for example, LCA models, suitable tools, data compilation, impact assessment, comparison of results, and need for new indicators/subcategories and a similar understanding of impacts between E-LCAs and S-LCAs [8,18,67,68].

Two contextual waves were identified when papers on LCAs began to be published (Figure 7). Each wave includes a period during which a focus was placed on the method itself (light grey) and a period during which an increasing number of case studies were published (dark grey). After a certain period of time, a topic, method, or approach has been described thoroughly enough (literature reviews begin to appear), and these might disappear. If they do not disappear, however, a new wave of this topic starts. The first wave of LCA started in the 1990s, the second wave started in the 2000s, and since LCA is a still a research field of increasing interest, a third wave is predicted. During this third wave of LCA research (Figure 7), social and economic impacts will be increasingly integrated in LCAs, and the methodology will be further developed and optimized. Therefore, this third wave is named as a "decade of consolidation." The prediction of this third wave is reasonable; our findings indicate that a period of LCA transition and an exciting time for LCA is coming [6,8,69]. Authors state that LCA is still under development [9,23,69] and that "a common system language for harmonization of various tools, methods, and disciplines is essential" to address challenges related to LCSA [18]. For example, it is still unclear where and how system boundaries should be determined and whether these should be consistent, e.g., when an LCSA is applied [23,47], although it is critical to define these boundaries. Additionally, Tarne et al. [47] mentioned that S-LCA currently has a comparatively low maturity level and that the presentation and interpretation of results need to be improved in their review on life cycle sustainability assessment and the potential for its adoption at an automotive company. These are examples which highlight the need for further LC(S)A development to integrate all sustainability aspects and generate an applicable (and eventually standardized) method.

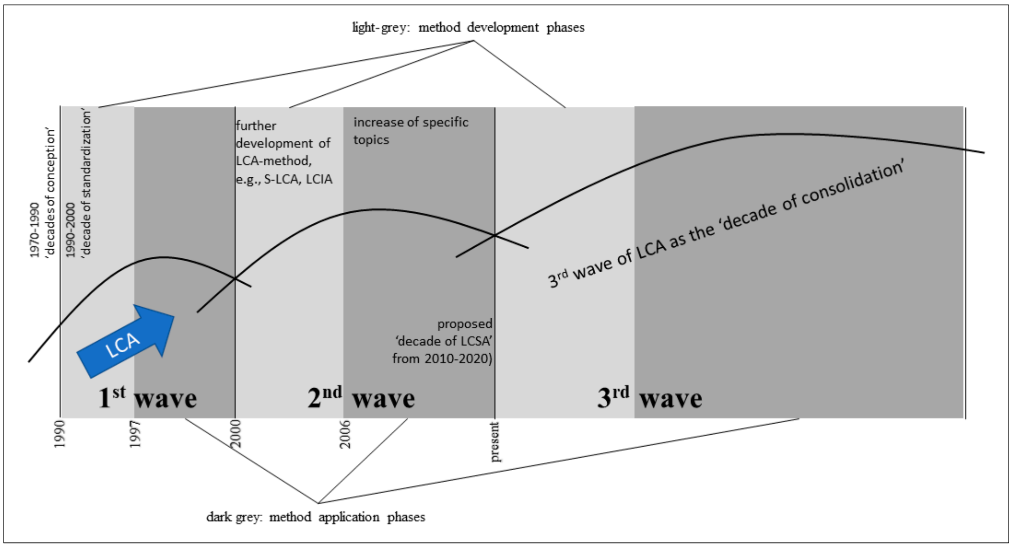

Figure 7. The three waves within the literature on LCA (third wave is predicted based on the results of the study and the assumptions of the research team). LCIA: life cycle impact assessment.

Forecasting such waves might help to promote important and necessary research fields. The third wave of LCA was initiated when the focus turned to method development, integrating the holistic perspective of sustainability (S-LCA, LCSA, integration of holistic sustainability perspective, temporal dynamics of sustainability, and geographical context in LCAs). Therefore, our results indicate that further method development is needed during the upcoming phases. In particular, all three sustainability dimensions need to be integrated. This aspect is highly challenging but also essential for the use of LC(S)A. More research on LCSA (method development and case studies) is needed regarding how to integrate the holistic sustainability perspective into the LCA approach. In addition, researchers need to understand which topics should be included and more strongly promoted in LCAs. One question that arose during the study was whether all sustainability topics had been covered sufficiently out of the 20 identified topics. It is important to answer this question in order to tackle unsustainable global developments. Research on LCAs and their application has progressed over the most recent decades; however, open questions and several challenges remain. This "third wave of consolidation" will be an important future development for LC(S)A.

6. Conclusions

LCA is a powerful assessment tool with a wide range of applicability, as can be seen by the topics and the number of publications identified in this study. The identified topics show that LCA is broadly applicable, as it was used in contexts such as transport, waste, cultivation, power, water, and mining systems. However, the range of topics identified shows that the focus of LCA research is still placed on environmental topics, although researchers have increasingly sought to integrate a holistic sustainability perspective in LCAs and have proposed the existence of a "decade of LCSA" from 2010 to 2020. A minor discussion of social aspects and a lack of discussion on economic aspects were identified in the present study. These results do not support the predicted "decade of life cycle sustainability assessment. The number of publications on LCA increased from 1990 to 2000 ("decade of standardization") and after 2006, which can be explained by the revision dates of the ISO 140140/14044 standard. This finding suggests that standardization of LCSA (or S-LCA as a first step) is crucial and, consequently, required to improve and optimize LCSA in the future. Therefore, the methods themselves need to be consolidated to, for example, standardize S-LCA. Once the assessment methodologies themselves have been consolidated (i.e., all three dimensions of sustainability are consolidated into one sustainability assessment method), the "decade of LCSA" can begin.

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Abbreviation

E-LCA	Environmental life cycle assessment
FSSD	Framework for strategic sustainable development
LCA	Life cycle assessment
LCC	Life cycle costing
LCIA	Life cycle impact assessment
LCSA	Life cycle sustainability assessment
PBA	Planetary boundaries approach
QALYs	Quality-adjusted life years
RQ	Research question
SETAC	Society of environmental toxicology and chemistry
S-LCA	Social life cycle assessment
SLCM	Strategic life-cycle management

Appendix A

Table A1. Overview of clusters of frequently co-occurring root nouns including manually labelled topics.

20 TOPICS in LCA-Abstracts										
Topic #	**Topic 1**	**Topic 2**	**Topic 3**	**Topic 4**	**Topic 5**	**Topic 6**	**Topic 7**	**Topic 8**	**Topic 9**	**Topic 10**
Name Topic	**Energy Systems**	**Water Systems**	**Mining Systems**	**CO_2-Emissions**	**Population**	**Infrastructure**	**Power Systems**	**Life Cycle Impact Assessment**	**Refinery Systems**	**Transport Systems**
First **10** keywords	energi electr power heat system generat wind pv hydrogen cell	water irrig desalin scarciti consumpt drink freshwat groundwat rainwat footprint	treatment wastewat sludg mine alloc copper eco-effici sewag metal zinc	carbon footprint CO_2 cement emiss dioxid cf tourism coinf tax	exposur risk growth popul remedi test age fate health concentr	design cost optim pavement mainten road model infrastructur perform network	coal air captur CO_2 pollut gas plant ccs nox power	impact deplet potenti acidif eutroph warm gwp ecotox ozon toxic	oil biodiesel palm diesel extract refineri rapese nois jatropha soybean	ghg gas greenhous fuel vehicl transport emiss gasolin reduct diesel
Most relevant **5** keywords from 20 left nouns	effici turbin storag kWh fuel	seawat rwh evapor precipit river	ore nickel silver phosphorus gold	equival industri CO_2e clinker consumpt	surviv toxic usetox mortal diseas	asphalt bridg traffic engin highway	methan ammonia SO_2 emiss combust	freshwat chang climat layer health	methyl distil ester sunflow petroleum	fleet car travel hybrid truck
15 remaining keywords	grid payback mix plant demand exergi oper analysi cycl technolog consumpt steam district chp silicon	m3 use coffe stress osmosi basin wf withdraw tank qualiti tio2 storm suppli catchment tap	remov wwtp lead plant recoveri discharg zn nanoparticl chromium process pb uv cr reactor reus	kg fli ef charcoal reduct tourist trade hotel sequestr eq limeston cfp co calcium cpo	temperatur reproduct effect size denisiti g/l degrad express control cd soil adsorpt rate host releas	program life-cycl analysi lcc problem paper servic plan algorithm life case approach rehabilit repair method	shale storag flue membran pe damag ss peat urin lignit technolog generat sulfur leakag co	categori assess lcia ep format ap studi lca characteris recip endpoint normal cycl eq kg	product refin cook seed process ahp transesterif tea cultiv canola glycerol lubric lc butanol veget	cycl passeng life consumpt energi ev use km mitig batteri transit polici intens combust rang

Table A1. *Cont.*

20 TOPICS in LCA-Abstracts										
Topic #	**Topic 11**	**Topic 12**	**Topic 13**	**Topic 14**	**Topic 15**	**Topic 16**	**Topic 17**	**Topic 18**	**Topic 19**	**Topic 20**
Name Topic	**Application Related to Products and Processes**	**Material Cycles**	**Construction Systems**	**Food Systems**	**Waste Systems**	**Lca Modeling**	**Biorefinery Systems**	**Application Related to Sustainability**	**Agricultural Systems**	**Cultivation Systems**
First **10** keywords	product	materi	build	food	wast	model	ethanol	sustain	land	farm
	process	steel	construct	chain	manag	uncertainti	biomass	develop	forest	kg
	life	aluminum	energi	suppli	landfil	variabl	feedstock	assess	milk	crop
	cycl	recycl	hous	product	inciner	analysi	product	framework	wood	fertil
	manufactur	concret	insul	packag	recoveri	method	biofuel	research	climat	product
	impact	iron	life	fish	compost	input	corn	approach	chang	feed
	inventori	scrap	roof	meat	collect	time	bioethanol	paper	bioenergi	manur
	assess	aluminium	wall	consumpt	scenario	sensit	pyrolysi	cycl	soil	nitrogen
	lca	flow	phase	wine	recycl	factor	process	life	biomass	dairi
	studi	eol	demolit	consum	dispos	sampl	convers	decis	use	wheat
Most relevant **5** keywords from 20 left nouns	paper	resourc	floor	aquacultur	msw	variat	sugarcan	lca	rice	cultiv
	material	remanufactur	materi	pork	digest	paramet	biorefineri	analysi	biodivers	n2o
	pulp	furnac	wool	beef	leachat	simul	gasif	concept	rotat	bioga
	textil	coke	concret	fruit	e-waste	output	biochar	applic	harvest	nutrient
	fibr	metal	brick	seafood	composit	estim	alga	tool	ecosystem	fertilis
15 remaining keywords	stage	strength	cycl	feed	treatment	character	sugar	inform	straw	diet
	phase	consumpt	offic	protein	system	pipe	energi	polici	forestri	ad
	use	product	thick	poultri	option	approach	fuel	industri	land-us	maiz
	methodolog	polym	consumpt	market	separ	emergi	stover	busi	tree	yield
	softwar	slag	use	produc	studi	accuraci	microalga	articl	sequestr	digest
	databas	glass	envelop	system	energi	probabl	jet	manag	graze	grain
	lci	industri	studi	commod	materi	distribut	synthesi	context	occup	pig
	method	durabl	refriger	val	fraction	film	methanol	review	carbon	anim
	iso	corros	frame	distribut	kiln	inventori	acid	case	willow	livestock
	analysi	fiber	light	bread	prevent	matrix	switchgrass	project	hectar	field
	order	manufactur	timber	sector	sort	regress	pretreat	eval	pastur	soil
	unit	reus	bus	fisheri	stream	pvc	cassava	implement	mitig	agricultur
	machin	substitut	window	anim	srf	error	pathway	literatur	intensif	system
	tool	blast	ventil	orchard	amount	lca	yield	innov	timber	ch4
	dispos	alloy	perform	chees	analysis	correl	bagass	level	fpcm	CO_2-eq

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