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CRITICAL REVIEW

Systematising the LCA approaches' soup: a framework based on text mining

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Abstract

Purpose It is challenging for practitioners to navigate through the multitude of life cycle assessment (LCA) approaches due to the rich literature and a lack of systematisation. The LCA flexibility allowed by standards results in a multitude of applications and, as referred to in previous works, as an "alphabet soup". This paper proposes a scheme for a clearer classification of currently used LCA approaches, with consideration of the 4-stage framework coming from standards.

Methods This systematisation was first established through literature research serving as a preliminary tentative framework. A text mining task was carried out in a second stage, involving 2044 published articles among 7558 of the last 10 years. For text mining, a dictionary collected keywords and synonyms of the LCA approaches. Such keywords were then extracted from the text together with their context (multiword). The final multiword analysis allowed the association of each keyword (i.e. each LCA approach) with a specific LCA stage (Goal and Scope, Life Cycle Inventory, Life Cycle Impact Assessment, Interpretation). The preliminary framework was adapted, further enriched and validated based on the text mining results.

Results As a result of the text mining activities, the preliminary tentative framework was partially confirmed and enriched with new insights, especially in the field of "explorative" LCA approaches, which also include "prospective" and "scenario-based" LCA. For most of the currently used LCA approaches, a link to a unique LCA stage was not recorded. However, clear trends were detected. The text mining task also highlighted a high number of works in which different approaches are compared or counterposed, especially in the field of attributional and consequential LCA. Some issues were found with the connotations of "traditional" approaches, which could be defined more specifically as "non-explorative".

Conclusions Unlike other works focused on notions from selected literature, text mining activities can provide bottom-up feedback on a larger scale more automatically. In addition, this work brought out novel LCA approaches, for which future developments will confirm a final definition and systematisation. As an additional advantage, the presented methodology is easily replicable. Hence, the presented framework can be updated along with developments in LCA approaches.

Keywords Life Cycle Assessment (LCA) approaches · Systematic Literature Review (SRL) · Text mining

Abbreviations

ALCA	Attributional Life Cycle Assessment
AI	Artificial Intelligence
CF	Characterisation Factors
CLCA	Consequential Life Cycle Assessment
DLCA	Dynamic Life Cycle Assessment
G&S	Goal and Scope
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
SLCA	Scenario (-based) Life Cycle Assessment
SLR	Systematic Literature Review
TRL	Technology Readiness Level
XLCA	Explorative Life Cycle Assessment

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1 Introduction

In applied sciences, operators are required to follow codes, regulations and standards. As opposed to codes, which set rules and recommendations for actions, a standard consists of technical definitions and guidelines that have the role of instructions for users (International Organization for Standardization 2021). In this sense, standards aim to set a common, consistent language suitable for repetitive use and can be characterised by a dedicated flexibility. This is the case for Life Cycle Assessment (LCA), a methodology whose framework, rules and guidelines are set internationally by the ISO 14040 and 14044 standards (International Organization for Standardization 2006a, b). LCA methodology offers different approaches to best fit the research question and organisation requirements. As stated in ISO 14040 (§ 4.3 e; g; h) (International Organization for Standardization 2006a), "the LCA methodology is open to the inclusion of new scientific findings and improvements in the state-of-art". As long as its scientific nature and objectivity persist, no unique method for conducting LCA applies to every situation.

A first well-known ongoing discussion in the literature is the differentiation (or division, by recalling Suh and Yang (2014) between attributional LCA (ALCA) and consequential LCA (CLCA), as two main LCA approaches, and the preference for one or another. While some authors argue for a clear distinction between the two concepts (Plevin et al. 2014), others plead for a "continuous spectrum instead of a dichotomy" (Suh and Yang 2014).

However, ALCA and CLCA are not the only two ways of dividing the LCA approaches into two. Newer techniques were developed to answer the need for LCA not only as a pure calculation tool but also as a basis for product development and decision-making under higher levels of uncertainty (Heijungs and Huijbregts 2004). Furthermore, in specific cases, such as buildings and building products with longer service life, *non-conventional* approaches have been developed to solve transparency and reliability issues (Ylmén et al. 2020; Di Bari et al. 2020) related to, e.g., the relative expression of potential environmental impacts to a reference unit, the integration of environmental data over space and time, the inherent uncertainty in modelling of environmental impacts, and the fact that some possible environmental impacts are clearly future impacts (Heijungs and Lenzen 2014). Through the inclusion of analytical, statistical and calculus instruments (Jolivet et al. 2021), the developed approaches ensure higher robustness of the results and adapt LCA to a broader spectrum of situations (for example, prediction of future conditions) (Heijungs and Lenzen 2014). In this regard, we can recall static LCA analyses, often counterposed to dynamic and probabilistic analyses. Static approaches consider a static life cycle inventory, i.e. a unique set of input flows to derive a unique set of output flows (Horn et al. 2018). As opposed to dynamic approaches, variabilities are disregarded. Compared to probabilistic approaches, in static approaches, uncertainties are handled through deterministic assumptions (Gantner 2017). Static impact characterisation models are usually considered as the basis for the life cycle impact assessment.

Finally, it may also be possible to group LCA approaches depending on their application in product development and the technology maturity, represented by the Technology Readiness Level (TRL) (Arvidsson et al. 2023). This led to the definition of "retrospective LCA" aimed at presenting (status quo) a product's environmental profile at the final stage of its development. They are retrospective in the way that they assess a product, which is already well defined and for which (already past) data were collected; therefore, it is praxis-based. By contrast, prospective LCA analyses consider future-based processes during product development and are therefore "future-oriented" (Guinée et al. 2018). Such approaches are characterised by an increased complexity related to the preparation of a wider set of inputs and output flows, the handling of a lack of information and the exploitation of statistical methods (van der Giesen et al. 2020). Different levels of uncertainty and variability assessment methods are also observed (Huijbregts 1998b). Moreover, within this realm of prospective studies, there are a multitude of approaches and designations. Pesonen et al. (2000) already reported the lack of general agreement regarding the names of such "future studies" or "prospective studies" (Pesonen et al. 2000). As LCA approaches, they mention, for example, extrapolating methods, exploratory methods, normative methods, etc., for which they tried to provide exemplary definitions.

Without going into the merits of such distinctions, finding an orientation among this multitude of approaches is no easy task, especially for non-experienced practitioners in non-mainstream LCA. Some authors have, however, already attempted to see more clearly this "alphabet soup of LCA" (Guinée et al. 2018) by providing definitions. While many focus on the notions of "ex ante", "anticipatory", and "prospective" LCA (Arvidsson et al. 2018, 2023; Buyle et al. 2019; van der Giesen et al. 2020; Villares et al. 2017), others also include additional concepts such as "dynamic" or "mixed" LCA (Cucurachi et al. 2018). Guinée et al. also tried to digest the soup by providing a comprehensive list of LCA approaches and their respective definitions, including "Scenario-based LCA", "integrated LCA", "backcasting LCA" and others (Guinée et al. 2018). They suggest classifying all of these LCA approaches under the umbrella term of "explorative LCA" (which includes CLCA). Based on their suggestion, the term "explorative LCA" will be used

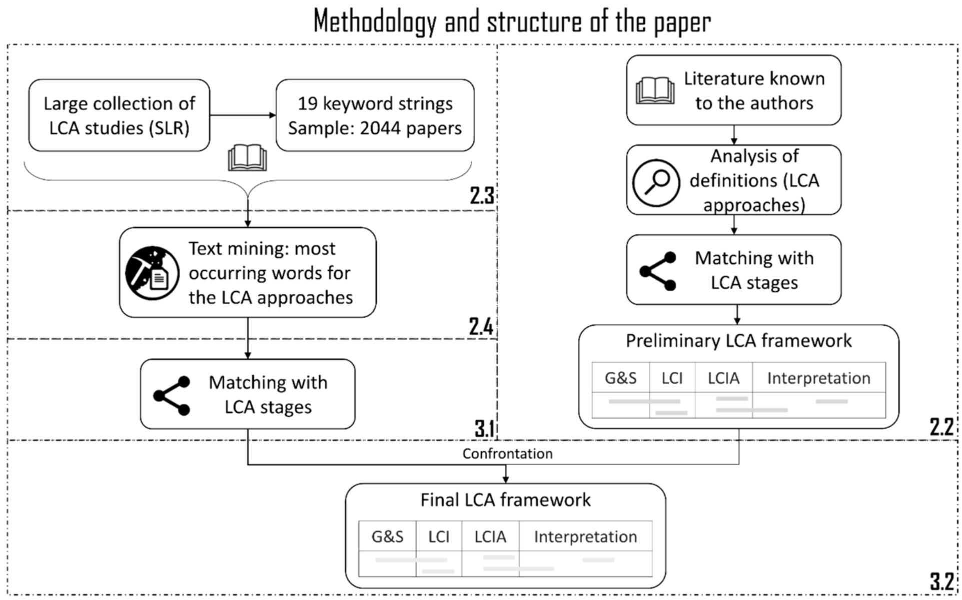


Fig. 1 Overview of the methodology and structure of the paper

in this paper to include all LCA approaches with a future-oriented approach, i.e. that are not "standard" retrospective LCAs. All of these approaches can be a priori, either attributional or consequential. The authors of this paper do not intrinsically perceive CLCA as future-oriented but rather as a perturbation of the current situation. Much like ALCA, it can either be retrospective or explorative (Joint Research Center - Institute for Environment and Sustainability 2010).

As a common characteristic, the definitions provided by the previously cited authors are usually based on a small number of reviewed papers and especially personal knowledge. However, they might not necessarily reflect large-scale trends in the LCA literature. On the contrary, this might reveal a sovereignty of perceptions in the literature. While papers such as the previous ones propose new nomenclatures, which may help LCA specialists see the LCA approaches more clearly, it is also essential to have a thorough and systematic view of the literature. For example, it could be argued that the nomenclature used in the literature by LCA specialists has more impact and relevance than the theoretical considerations of a restricted group of authors. In other words, a confrontation of theoretical knowledge with the LCA literature on a larger scale has the potential to enrich and enlighten the nomenclature of LCA approaches.

This work aims to provide a systematisation of LCA approaches under consideration of the 4-stage framework, analogous to other frameworks provided in the literature (Huijbregts 1998a). Systematic characterisation needs to reflect the perceptions of the literature, as well as the concrete applications in the field of LCA studies. Therefore, a preliminary ideal framework is created based on a restricted number of relevant papers. Afterwards, a larger number of works underwent a text mining process. In this work, text mining refers, more precisely, to text data mining. This process can be associated with text analytics and the automated derivation of information from text through machine learning and artificial intelligence techniques. Based on previous applications, text mining allowed proof of the initial concept and further enrichment of the framework in this work. Despite the challenges related to the Artificial Intelligence (AI) setup, as an advantage, this technique allowed faster and automated extraction and interpretation of large amounts of text in their context. The automatic parsing of textual corpora can extract actors and their relational networks on a vast scale, turning textual data into network data. Last, as also required in this work, it enabled text clustering and, therefore, data structuring.

2 Methodology

This section presents a detailed description of the applied investigation process (Fig. 1). Section 2.1 presents the fundamentals of the established framework with respect to the LCA standard (International Organization for Standardization 2006a, b). Based on this, Section 2.2 outlines a preliminary theoretical LCA framework, which takes into account relevant sources mentioned in the introduction. Section 2.3 describes the extensive systematic literature search (SLR) performed. Next, the text mining approach that allowed for the analysis of these retrieved articles is explained in Section 2.4. Finally, the initial framework is confronted and enriched based on the results of the SLR and text mining (Section 3.2). Similar procedures can be found in other works (Cordella et al. 2023), which are, however, related to different research fields.

2.1 Fundamentals for a systematisation of LCA approaches

Ideally, a selected approach covers and affects all main stages belonging to the LCA framework: goal and scope (G&S), life cycle inventory (LCI), life cycle impact assessment (LCIA) and interpretation. This is due to the iterative nature of the standard framework (International Organization for Standardization 2006a; Ortiz et al. 2009). However, looking at the definition of each approach in detail, a specific stage and/or, going into even more detail, a particular element of an LCA stage can be distinguished. For instance, among LCA approaches, probabilistic LCA is defined as "Analysis in which the **input** flows within the lifecycle **modelling** are represented stochastically, i.e. through probability density functions" (Favi et al. 2017). The definitions clearly recall, in the first instance, the semantic field of "input" and "modelling", i.e. the LCI. The product or process definition is part of the G&S stage, while the modelling part is part of the LCI. In summary, the terms used within a definition or often coappearing terms can be analysed. A semantic field can be detected and associated with a stage belonging to the LCA framework.

This concept can also sometimes be proven through the mathematics behind LCA. Frequently, LCA results have been represented by the calculation of the vector r of the environmental impacts according to (1):

$$\boldsymbol{r} = \boldsymbol{Q} \times \boldsymbol{H} \times \boldsymbol{G}^{-1} \times \boldsymbol{u}, \tag{1}$$

where Q is the matrix of characterisation factors (part of the LCIA), H is the environmental intervention matrix of emissions per unit process of product systems (LCI), G is the technology matrix representing the inter-process flows needed for the functioning of the product system (LCI), and u is the external supply (or final demand) vector, representing the functional unit (Sherwood et al. 2017) and dimension of which is related to the defined set of economic flows (G&S) (Heijungs and Sun 2002).

Figure 2 shows how static, dynamic and dynamic + scenario-based approaches can be associated with the single LCI stage and, algebraically, with the G matrix. When a static approach

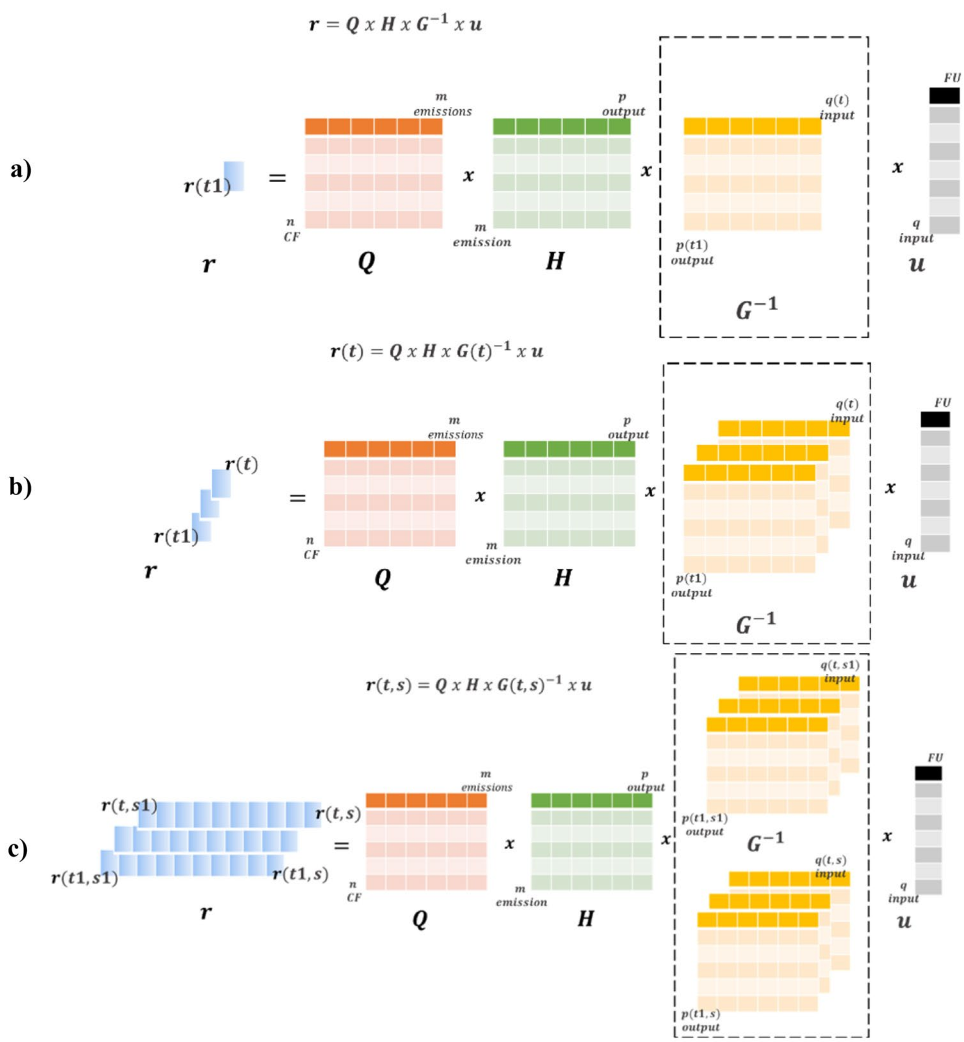


Fig. 2 LCA approach influence on LCI. Examples of **a** static, **b** dynamic, **c** dynamic + scenario LCA

is chosen for the products and processes' life cycle modelling, a single set of input and output flows is provided. Dynamic approaches enlarge the LCI matrix with a wider set of inputs and outputs depending on a parameter expressing variability (e.g. time, parameter t in Fig. 2). LCI can be further enlarged if scenarios (parameter s in Fig. 2) are included, which consequently enriches the set of provided results. Moreover, Levasseur et al. proposed an approach that entailed the calculation of characterisation factors (CF) on a yearly basis (Levasseur et al. 2010). This approach affects the LCIA stage and, algebraically, the Q matrix (Fig. 3). Theoretically, all matrixes can be expanded and filled with the help of different tools, which can determine the LCA approach.

The authors of this paper recognise the simplified character of such an algebraic calculation. However, it is important to underline that, as also stated in Heijungs (2020), simplifications and subterfuges are used for modelling purposes: LCA has a multilinear, i.e. non-linear, character that lies on feedback loops, e.g. closed loop recycling and non-linear industrial processes. As also stated by Heijungs, the weaker property of multilinearity allows for the homogeneity of the LCI and for the possibility of solving via linear algebra (Heijungs 2020).

2.2 Preliminary LCA framework

As a first step in this work, a preliminary framework for LCA approaches was established. The nomenclature and definitions for each approach are primarily based on the results from a review paper on LCA approaches (Guinée et al. 2018) (see Table 1). The nomenclature of predictive and static LCA, since missing in the abovementioned work, is based on exemplary applications. Starting from definitions, keywords are emphasised in italics. The extracted keywords are finally linked to an LCA stage depending on their semantic field, as explained in Section 2.1.

As a result of this literature review, the preliminary framework is developed. Figure 4 collects and synthesises the outcomes presented in Table 1. Each LCA stage is represented and accompanied by the respective vector or matrix, according to Section 2.1. Finally, all approaches are collected and classified depending on how they might affect the LCA algebraic calculation. Please note that approaches, such as attributional and consequential LCA, can involve more than one LCA stage and, therefore, potentially affect more than one vector or matrix (depending on each case's complexity).

The interpretation and communication of results are related to the final r vector. Results interpretation and communication entail, e.g., visualisation strategies and are critical for supporting decision-making (Sala and Andreasson 2018). In this regard, approaches can be developed depending on the complexity of the results: it can assume a more straightforward vectorial form, whereas no variabilities and uncertainties are considered. In this case, an impact is represented by a single value. More discrete values or a range of values can be presented when a scenario, dynamic or probabilistic modelling occurs (see Figs. 2 and 3).

As also mentioned in Section 1 and shown in Fig. 2c, a selected approach does not exclude the possibility of considering another one. In this instance, mixing several approaches in the same LCA analysis is possible. Explorative LCA, e.g., can rely not only on a scenario-based LCA but also enhance the analysis with consideration of variabilities and uncertainties. Therefore, dynamic or probabilistic lifecycle modelling can be exploited. This concept can also explain why, at least in theory, ALCA and CLCA might be understood as a "continuous spectrum" instead of a dichotomy.

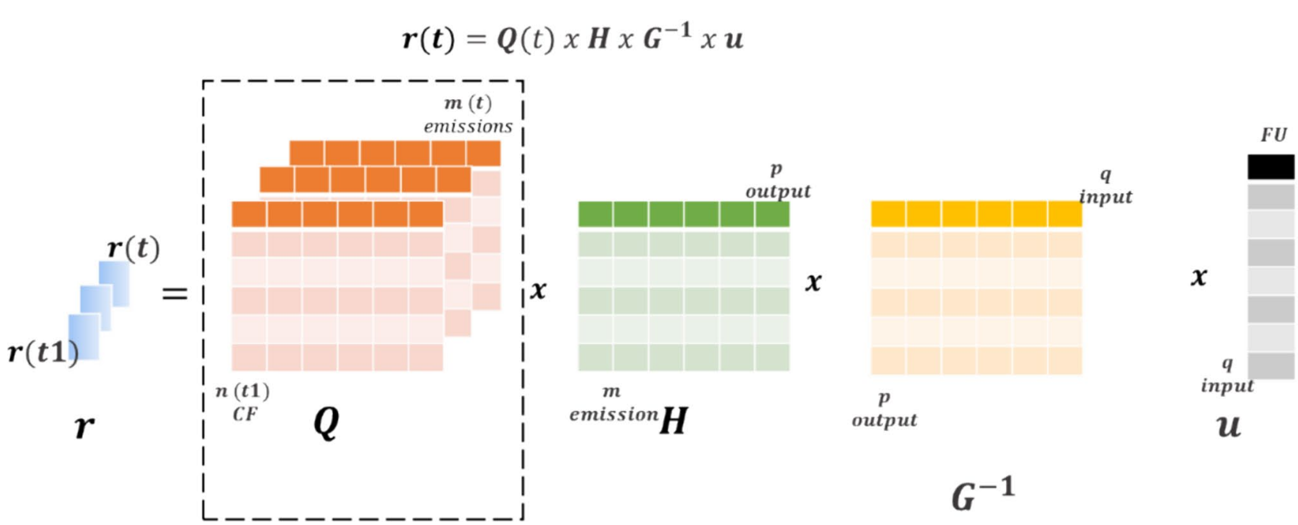


Fig. 3 LCA approach influences LCIA. Examples of dynamic approaches (dynamic CF)

Table 1 Summary of LCA approaches and definitions according to Guinée et al. (2018)

Approach	Definition	Keywords	LCA stage
Attributional (ALCA)	Approaches aimed to *trace a specific aspect* of the *product* (as determined by the allocation rule) back to its contributing unit processes. System *modelling* in which *inputs and outputs* are attributed to the *functional unit* of a *product system* by linking and/or partitioning the unit processes of the system *according to a normative rule* (Sonnemann and Vigon 2011).	Product System Functional unit Model Input, Output	G&S LCI
Consequential (CLCA)	Approaches aimed at decision support. In a *system*, consequences are traced forward in time. *System modelling* approach in which activities in a *product system* are linked so that activities are included in the *product system* to the extent that they are expected to change as a consequence of a change in demand for the *functional unit* (Sonnemann and Vigon 2011).	Product System Functional unit Model	G&S LCI
Explorative (XLCA)	*Future-oriented* analysis aimed to explore potential futures through *future processes/products* and their respective scenarios. This umbrella term covers different approaches (Guinée et al. 2018): - Prospective LCA - Ex-ante LCA - Backcasting LCA	Product (potential/future)	G&S
Retrospective	Retrospective LCA provides information about the environmental properties of a *past or current* life cycle investigated and of its *subsystems*. (Ekvall et al. 2005)	System (past/current)	G&S
Predictive	Analysis, whose *modelling* is carried out through predictive tools, e.g. agent modelling, game theory, machine learning and Gaussian Process Regression (Karka et al. 2019)	Model	LCI
Scenario-based (SLCA)	LCA based on scenarios separating three *modelling* processes: life-cycle *modelling*, scenario *modelling*, and valuation *modelling* (Fukushima and Hirao 2002)	Model	LCI
Probabilistic	Analysis in which the *input flows* within the lifecycle *modelling* are represented stochastically, i.e. through probability density functions (Favi et al. 2017).	Input flows model	LCI
Dynamic (DLCA)	Analyses, which incorporate spatial/temporal variations of the *input flows and emissions* into the assessment.(Su et al. 2021).	Input flow Emission	LCI LCIA
Static	LCA, in which variabilities of *inventory* and *emissions* are neglected (Lueddeckens et al. 2020).	Inventory Emission	LCI LCIA

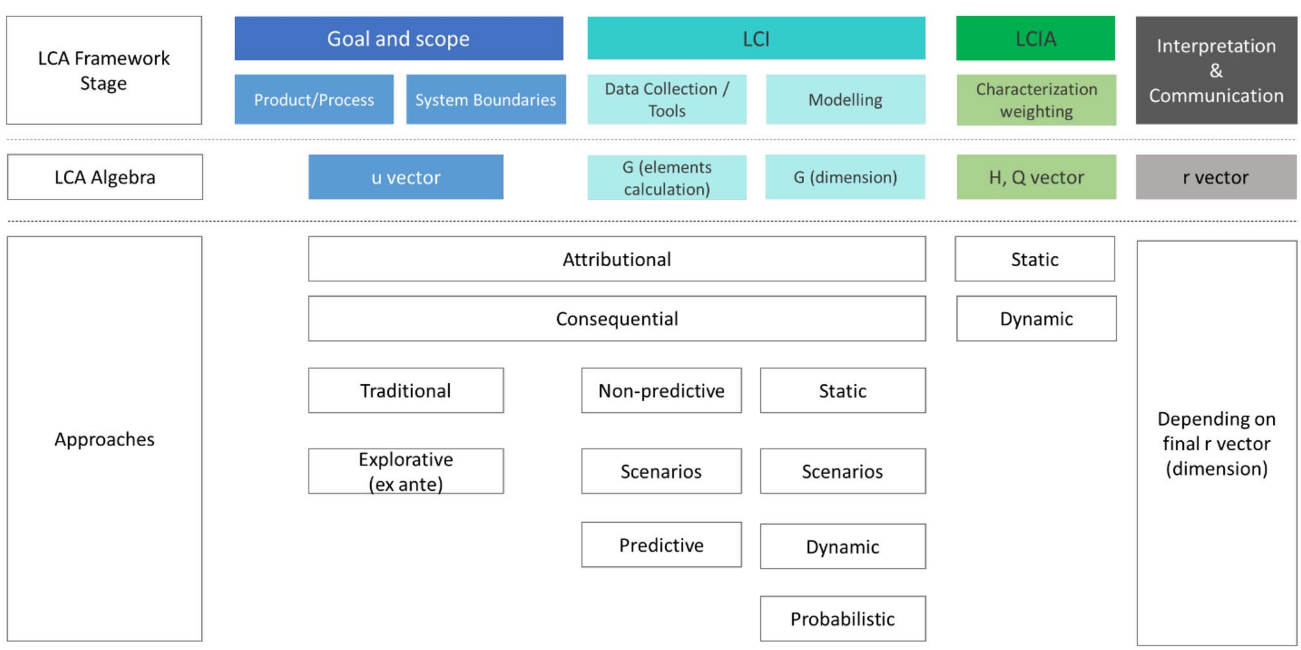


Fig. 4 Preliminary tentative structure for a classification of LCA approaches

2.3 Systematic literature search

A second step of this analysis was to perform a systematic literature search to collect a large number of relevant papers for the text mining approach. The authors wished to include papers focusing on LCA approaches, whether discussed or applied to a case study and to reflect the large number of terms used to designate these approaches (as mentioned in the introduction). For that purpose, keyword strings were generated in the following way: *keyword* AND ("life cycle a*" OR LCA) in which the *keyword* was alternatively replaced by *dynamic, prospective, ex-ante, explorative, anticipatory, backcasting, early-stage, emerging, screening, retrospective, ex-post, static, predictive, scenario-based, probabilistic, stochastic, time dependent, attributional, consequential.* In other words, 19 keyword strings were used, the first one being "dynamic AND ("life cycle a*" OR LCA)", the second one "prospective AND ("life cycle a*" OR LCA)", etc. This extensive list of keywords reflects the designation for LCA approaches that were observed by the authors in future-oriented LCA papers (Arvidsson et al. 2018; Buyle et al. 2019; Cucurachi et al. 2018; Guinée et al. 2018; van der Giesen et al. 2020; Villares et al. 2017), some of them being presented in the introduction.

The search was performed in July 2022 using the "Article title, Abstract and Keywords" section of the Scopus database. Scopus is especially well suited for the purpose of this study, as it hosts a large number of papers relevant to the fields of LCA, sustainability and applied sciences. The search was limited to English peer-reviewed papers published in the last ten years. The reason for excluding papers older than ten years is that especially explorative LCA approaches have seen increasing interest in the past ten years, but the idea was also to avoid conflicting understandings or views regarding some of the approaches. For example, the term "prospective LCA" was long used to designate "consequential LCA", and in the past, the distinction between the two was unclear or confused (Tillman 2000). Such misunderstandings between "older" and "newer" definitions are aimed to be limited with this 10-year cutoff.

When performing the search according to the above-described procedure, a total of 7885 papers were collected. The first step was to automatically delete duplicates using the references manager, which led to the exclusion of 950 papers. Among the 6935 remaining articles, the titles of the articles were read, and those that did not focus on LCA or sustainability or came from journals that did not address such topics were further deleted. After this second round of screening, 3481 articles remained. The abstract was read for each article, and the article was only kept if there was a focus on LCA (regardless of whether it was a review paper, a case study, or other). After this next round of elimination, 2156 articles remained for text mining. However, the authors did not have access to all of these articles and, therefore, could only use 2044 of them for text mining. The size of the final sample of articles is still statistically significant to ensure the quality of the text mining analysis (Duck et al. 2016). A summary graph of the approach followed for the systematic search is provided in Fig. 5.

2.4 Text mining approach for analysing the sample of papers

Text mining (also called text data mining) is a process similar to text analytics, in which information is derived from the text. Its process consists of structuring an "input text" by selecting or removing linguistic features and, as a result, creating a final database. Such a database allows for a pattern derivation within the structured data, which can be evaluated and interpreted. Typical text mining tasks include text categorisation, text clustering, concept/entity extraction, production of granular taxonomies, sentiment analysis, document summarisation, and entity relation modelling (i.e. learning relations between named entities) (Hearst 1999).

Text mining examples can be found in various fields for research and business needs (Paltoglou and Thelwall 2012; Zanasi 2009). In the field of LCA, text mining has already been used for the creational Terminological Inventory for Biodiversity and the Biodiversity Search System (Batista-Navarro et al. 2017) and to identify relevant methods and review publications on land use. Furthermore, recent work has exploited a text mining technique in order to carry out literature research on Life Cycle Sustainability Assessment (LCSA) and to identify key challenges as well as the need for a consistent and operational link between LCSA and Sustainable Development Goals (SDGs) (Cordella et al. 2023).

One of the most applied text mining techniques and tools is used for "text analytics", which means counting the frequency of words in a large number of texts (Duriau et al. 2007; Short et al. 2010). When text analytics is carried out by combining keywords of a specific topic, this technique can be used as a systematic tool for a large number of papers to be reviewed (Ciano et al. 2019). In particular, (further analysis of) co-occurrence of keywords can unlock quantitative correlations among the approaches (Ciano et al. 2021). When the texts in a paper refer to pre-defined LCA approach terms, the paper is flagged as dealing with the specific LCA approach. The pre-defined LCA approach terms are extracted and counted as data for further analytics.

The following steps can explain the text mining applied in this work:

1. **Pre-processing**: cleaning and tokenisation of the dataset (collection of the relevant documents from the previous section). The initial text needs to be pre-processed

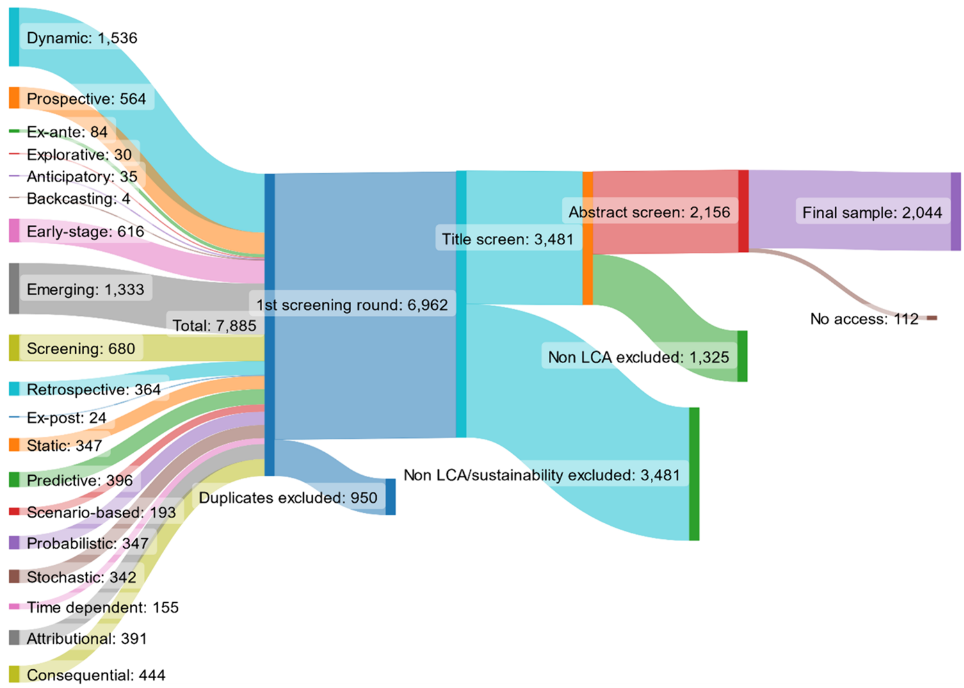


Fig. 5 Overview of the procedure followed for the systematic literature search. The far-left side of the graph gives information on the number of papers found in the literature with each keyword (total of 7885). After excluding duplicates, 6935 remained. Through the successive reading of the titles ("title screen") and abstract of each paper ("abstract screen"), non-sustainability or LCA-specific papers were excluded. The final sample, as shown on the far-right side of the graph, consisted of 2044 papers

by unifying different forms with the same meanings for grammatical reasons. For example, "ex ante", "ex-ante", and "exante" should be counted as one meaningful word. Without the pre-processing, the text mining tool counts each term separately. Additionally, lowering the cases, removing the list of references, numbers, URLs, special characters, as well as stop words (i.e. common words with less meaning such as an article, prepositions, pronouns, conjunction words). Abbreviations with all-uppercase characters are kept. Cleaning and tokenisation were executed by the Quanteda R package (Benoit et al. 2018).

2. **Dictionary creation** keywords and synonyms of the approaches are collected by the authors based on the work of (Guinée et al. 2018), as shown in Table 2. Note that some keywords might miss their endings. This is due to the pre-processing, in which some suffixes are deleted (e.g. backcasti, which stands for backcasting). Some other keywords' endings are not entirely deleted (e.g. consequential). All keywords referring to the approaches should be unique enough to be linked to the approaches without coinciding with the name of the approaches.
3. **Keyword extraction**: This is carried out with the help of the Quanteda R package (Benoit et al. 2018), including a statistical extension model called "textstat_collocations" model (Quanteda version 2.1.2). The choice of such a model also allows internal error testing based on the automatic asymptotic standard error verification (Blaheta and Johnson 2001).

Table 2 Dictionary creation for LCA approaches text mining (step 2)

Keyword	Synonym						
consequential	CLCA	C-LCA					
attributional	ALCA	A-LCA					
explorativ	XLCA X-LCA	Ex-ante exante ex ante	anticipator	backcasti	screeni	prospectiv	emerg
retrospectiv							
dynamic	time-dependent	DLCA	D-LCA				
static							
probabilistic	stochastic						
predictiv							
scenario-based	scenario	SLCA	S-LCA				
retrospectiv	Ex-post						
traditional	standard	conventional	mainstream				

Table 3 Results of text mining and stage attribution

	Co-occurrences counted	Comparison/ Union approaches	G&S	LCI	LCIA	Int	Attributed Stage
Attributional	1930	54.15%	10.83%	26.48%	8.55%	0.00%	**LCI** G&S
Consequential	1730	20.75%	16.59%	56.36%	6.30%	0.00%	**LCI** G&S
Explorative	629	22.26%	64.39%	9.22%	4.13%	0.00%	**G&S**
Traditional	252	48.81%	39.68%	11.51%	0.00%	0.00%	**G&S** LCI
Scenario	5170	16.21%	42.46%	22.71%	15.22%	3.40%	**G&S** LCI LCIA
Dynamic	2612	5.78%	15.93%	41.00%	37.29%	0.00%	**LCI** **LCIA** G&S
Static	496	46.57%	15.32%	25.00%	13.10%	0.00%	LCI G&S LCIA
Probabilistic	588	6.63%	18.37%	65.48%	9.52%	0.00%	**LCI**
Predictive	591	7.61%	17.26%	52.28%	22.84%	0.00%	**LCI**

4. **Counting of keywords and ranking of co-occurrences per paper**: Keywords in the papers are counted based on the dictionary (Step 2) and results collected (see Table 3 in Section 3.1). The count is recorded as many times as the keywords and synonyms are found in a single paper. The ranking occurs by considering the Wald test z-statistic and according to (Blaheta and Johnson 2001). Co-occurrence of the key terms means that the unique two or three words are written within a four-word distance, and the co-occurrence matrix is created to calculate the distance between two unique words.
5. **Mapping the interrelations in the framework**. For the interpretation of results, an equal importance weight was allocated to each keyword.

The limitations of text mining in data mining are mainly related to the primary or perform-related data rather than the technology or the algorithm-related data. Since the algorithm is used only for (multi-) keywords counting, the performed analysis on the whole context could be missed. To overcome this potential issue, the pre-selection of previous articles is an essential task. Still, developers are working on this issue in order to apply a more complex processing model in the future. Furthermore, looking at the applied approach and potential model-specific limitations, the counting collocations model does not consider the length of the text. When one document is much longer than the others, the longer text has more statistical opportunity to have a larger number of repeating keywords. However, the data sources used for this paper are solely scientifically published journal papers with a similar specified number of pages.

3 Results and discussion

3.1 Text mining results and attribution of an LCA stage

In this section, the results from text mining are reported and are aimed at enriching the preliminary framework defined in Sect. 2.2. The evaluation of terms' co-occurrence (also called multiword) has been carried out in a first instance up to 4 words' distance.

The final derived table, found in the Annex, contains the following information (metadata):

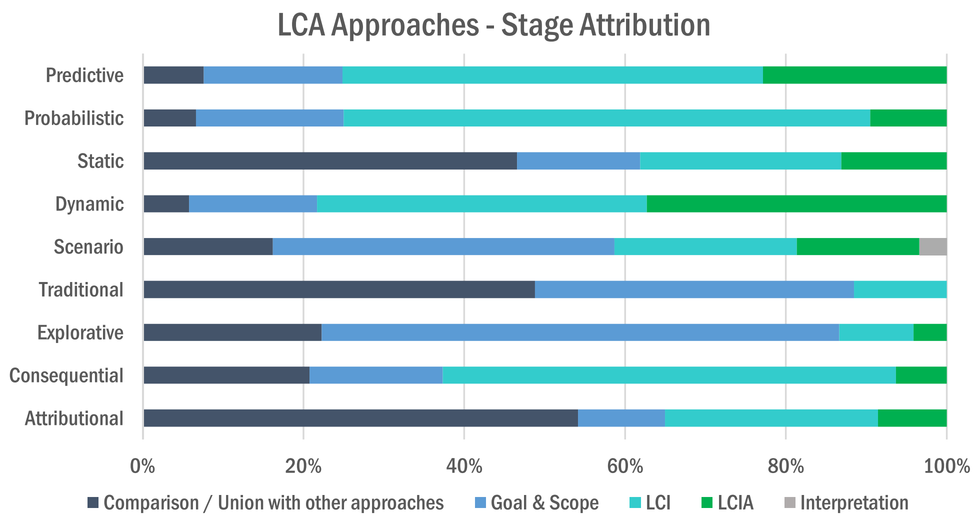
- An index of each multiword
- The multiword ("collocation")
- The counted amount of multiword
- A nested count
- The length "Lambda" and the value "z" represent parameters used for the co-occurrence ranking according to the z-statistic used approach (Blaheta and Johnson 2001).

In total, the software collected the following:

- 134883 multiwords of 2 terms
- 3614 multiwords made of 3 terms
- 1769 multiwords of 4 terms.

From the column "Collocation", multiwords presenting relevant keywords have been filtered and selected, as established in the dictionary (Table 2). After this selection, the results were analysed, and non-relevant multiwords were excluded. This occurred especially if the keyword was

Fig. 6 Results of text mining and stage attribution



followed by words that were too generic (e.g. approach, study, environment, framework). Table 3 presents a summary of the analysis carried out for the LCA stage attribution. For the sake of completeness, relevant data generated or analysed during this study is included in this published article (Annex). In contrast, complete datasets generated during the current study are made available by the corresponding author upon reasonable request.

The authors decided to attribute an LCA stage when the counting of the association between a term and an LCA stage was higher than 10%. This was done in order to establish a threshold for significance. A unique stage is attributed only with at least 50% co-occurrence frequency. Where, however, the highest frequency lies in the comparison/union of approaches, other significant stages are considered (with at least 10% frequency). If one of those steps has a frequency of at least double than that of the others, it represents a preferred attribution (bold in Table 3).

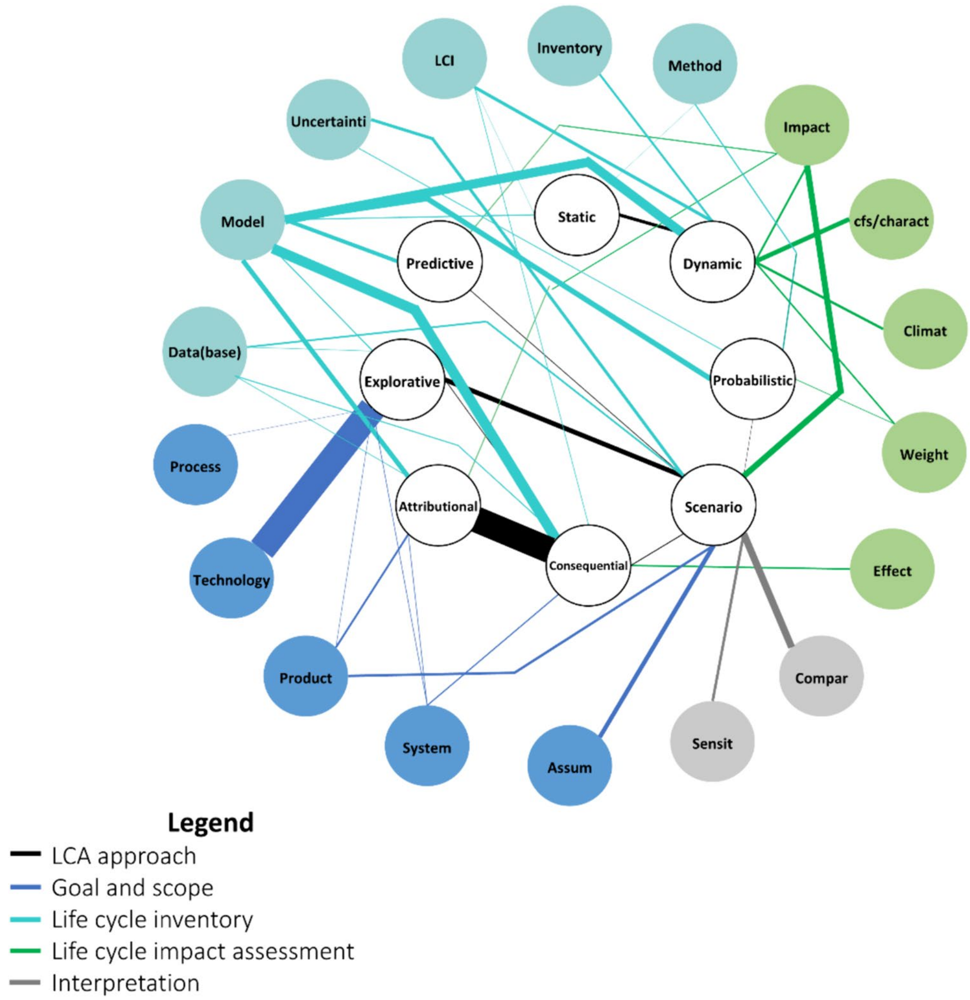
For attributional and consequential LCA, the analyses on the coappearances with up to 4-word distance associated such approaches with G&S (with words such as “products”, “processes”) and LCI (“Model”, “LCI”) (see Fig. 6). In the case of explorative LCA approaches, the most frequently repeated and coappearing words belong to the semantic field of Goal and Scope. More interestingly, the 4-Words’ distance analysis associated the keywords “ex-ante” and “prospect” with “emerging technology” (10 times in “ex-ante” and 11 times in “prospect”) (see the Annex and Fig. 7). This analysis helps to understand how explorative LCA approaches are and, among them, how prospective approaches refer to products and processes still under development (emerging technologies). The text mining and the analysis of the keyword “probabilistic” showed that most of the coappearing words belong to the semantic field of LCI since they mostly work on modelling and, hence, on inventory. Furthermore, such a keyword is often associated with uncertainties. This confirms, as expected, that probabilistic approaches provide tools for handling LCA uncertainties.

In the instance of dynamic LCA, there are slightly more than half of the cases in which the approach can be linked to the LCI stage, and nearly 40% of cases are attributed to LCIA. The keywords “dynamic” and “time-dependent” are associated with “Model” and, more clearly, with LCI and Inventory. It sometimes refers to the characterisation (“CFs”, “Character”) and weighting steps belonging to the LCIA (see Fig. 7).

Another interesting result relates to the frequent coappearance of 2 different approaches, either coming from a comparison or a union. In the instance of consequential and attributional LCA, the association “consequential attributional” is one of the most frequently recorded co-occurrences. This may be related to the numerous comparative assessments and review papers on attributional and consequential LCA analyses. The keyword “static” also has similar outcomes. According to the results, static LCA does not have a clear stage attribution, but is mainly used for comparison with other approaches, such as dynamic ones. The association “static dynamic” is very frequently recorded and this means that most of the research works presenting dynamic approaches compare results with static ones (and vice versa). Analogous to the keyword “dynamic”, “static” appears with words mostly belonging to the semantic field of LCI, while LCIA has a lower frequency (see Fig. 7).

With regard to “retrospective” LCA approaches (included in the Dictionary, see Table 2), text mining was not able to provide a link to a specific LCA stage. Except for the recurring coappearance of retrospect data, which may be linked to the LCI, retrospective as a keyword seems to be accompanied mainly by its opposite “prospect”, which is included in the umbrella term “Explorative LCA”. However, “retrospective” is not accompanied in any of the founded papers by the keyword “explorative”. In other words, in research papers,

Fig. 7 Results overview. LCA approaches, frequent co-occurrences and stage attribution



"retrospective" cannot be deemed the opposite of "explorative" LCA. Overall, this particular analysis presented less frequently counted repetitions, reflecting a lower number of papers found during the literature research process and the seldom usage of "retrospective" in the language of the LCA community.

Based on this last observation, in order to eventually seek an opposite term to explorative approaches and acknowledge non-explorative approaches as "traditional" and "mainstream", a text mining analysis on the keywords "tradit" (meaning traditional) and "mainstream" was carried out. As a further synonym of traditional, "standard" was excluded due to its higher probability of being referred to LCA ISO standards. As a result of this analysis, a higher frequency of "*traditional LCA*" and "*traditional approach*" was found. However, some research works refer to "traditional LCA" as attributional LCA or static LCA. Some authors prefer "*classic LCA*" instead of the "traditional" adjective; one paper only preferred "mainstream LCA".

3.2 Overview of the final LCA scheme — comparison with the previously established nomenclature

After carrying out the text mining process on the downloaded research papers, the preliminary tentative framework was enriched with new insights. More specifically, it is now clear (in Fig. 8 fields marked with light-green colour) that:

- Explorative LCA approaches focus on the process and products to be analysed and therefore belong to the goal and scope.
- Attributional and consequential LCA are more frequently referred to the LCI, even if there is a significant amount of work that relates them to the G&S.
- Static and dynamic approaches are opposite and focused on life cycle models, therefore belonging to the LCI.
- Dynamic characterisation factors and weighting have also been explored in LCA research. Therefore, dynamic

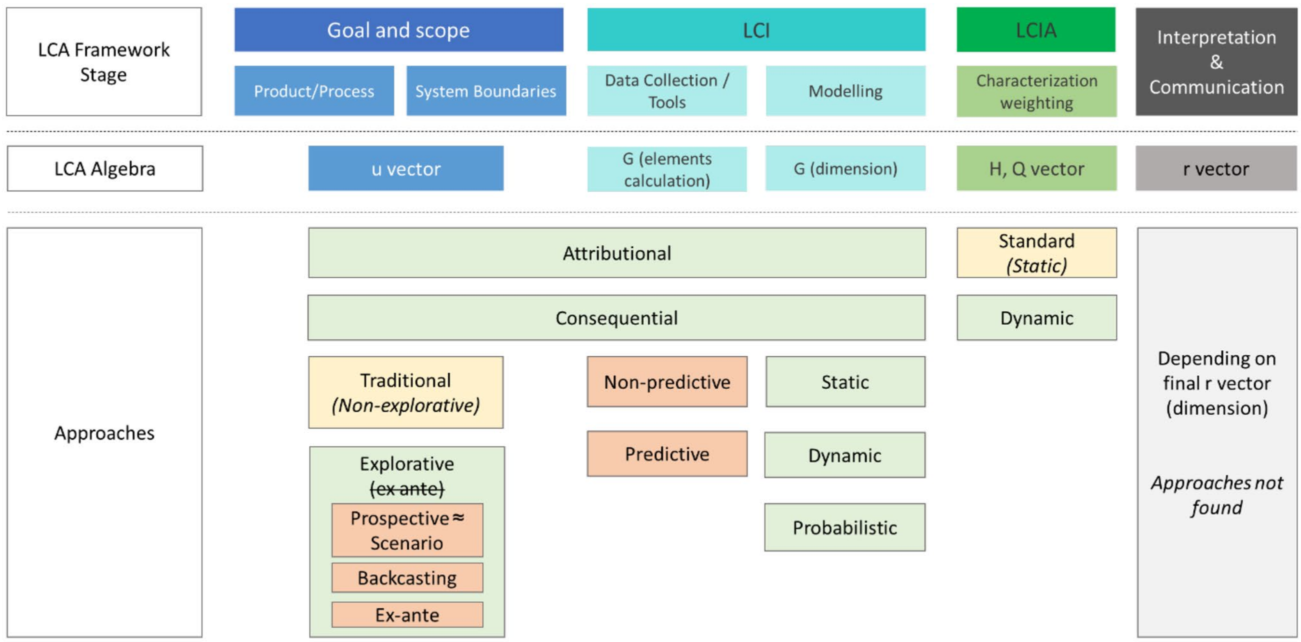


Fig. 8 Final framework for the attribution of the LCA approaches to the LCA stages

approaches can also be referred to as the LCIA stage. By contrast, "static LCIA" also seems to be appropriate, despite not being found in the literature.

- Probabilistic/stochastic LCA relates to life cycle modelling and therefore to the LCI.

In comparison with the preliminary framework, some variations and discussion points are found. When the variation involved the connotation only, it is marked as yellow in Fig. 8. Fields marked with red refer to cases for which variations or issues in terms of LCA stage attribution are also found.

- As opposed to the tentative framework, the connotation "traditional" is more widely used in the literature when referring to static LCA approaches. This connotation should hence be revised and eventually substituted with a more specific "non-explorative" LCA approach.
- Scenario (-based) LCA seems to cover a wider range of approaches aimed at investigating different products (G&S), life cycle models (LCI) and impacts (LCIA). In other words, scenario-based LCA approaches can be aimed at exploring different product options and, in this sense, can be seen as "prospective LCA", i.e. "explorative LCA" approaches. As a consequence, they can also affect the LCI and LCIA stages.
- Within explorative LCA, prospective, backcasting, and ex ante (anticipatory) LCA are now included. Research works on such approaches are not largely available.
- Research works on predictive LCA approaches are not largely found. Predictive approaches, as assumed within the tentative framework, predict the life cycle model. They can be allocated to the field of LCI-bound approaches, focusing on the tool for deriving a lifecycle model. By contrast, "nonpredictive" approaches (or other more suitable nomenclatures) can be located despite their lack of acknowledgement in the literature.

Due to a low number of research papers, characters and features need to be further investigated for both explorative and predictive approaches to back up or revise their positioning in the framework.

4 Summary and conclusion

Differences among LCA approaches are a recurrent discussion topic in the LCA community and review papers. Most of them focus on the identification of clear differences by establishing dichotomies, in which, e.g., attributional and consequential LCA (Plevin et al. 2014) or prospective and retrospective LCA (van der Giesen et al. 2020) are counterposed. Other authors provide a broader prospect, by pleading a continuous spectrum of LCA approaches (Suh and Yang 2014). Finally, Guinée et al. (2018) have published an extensive compilation of nomenclature and definitions of LCA approaches. Differently from other works, this one provided a first complete overview of current trends in the field of

LCA. However, the definition of approaches has not been accompanied by a more systematic classification, which is currently still lacking. Systematising LCA approaches can help practitioners to orient themselves and find the best corresponding approach. Furthermore, like most of the current review papers, the work of Guinée et al. (2018) is based on a small number of reviewed (relevant) papers and personal knowledge, yet it might not necessarily reflect large-scale trends in the LCA literature. A literature review requires significant time and resources investments, especially when carried out on large text corpora (Williams et al. 2021). In such cases, algorithms and tools are needed to allow a higher automation level and significantly reduce practitioners' efforts (van Dinter et al. 2021).

These issues are addressed with the procedure presented in the work, which presents a conceptual framework for systematising the multitude of approaches on trends in the LCA community and research. The applied methodology employs, as a novelty, metadata coming from text mining and, more specifically, text analytics for the attribution of an LCA approach to specific stages belonging to the LCA main framework (International Organization for Standardization 2006a). For this research, a large text corpus (2044 journal papers) was used, and the text mining technique was aimed at counting and selecting relevant co-occurrences of keywords. The unlocked quantitative correlations between LCA approaches and stages were allowed by the automatic counting of co-occurrences (also called multiwords) and their evaluation. The results from the text mining activities fed back an improved preliminary framework, which was produced based on the authors' experiences and perspectives.

The text mining confirmed, e.g., the focus of explorative LCA approaches on the process and products and therefore on the goal and scope. Static and dynamic approaches seem to be used as opposite terms with a focus on lifecycle models and, therefore, on the lifecycle inventory, as well as probabilistic/stochastic LCA. Ideally, dynamic LCA can be intended for LCI and LCIA (characterisation and weighting) but applied more often in LCI. As opposed to the preliminary framework, text mining allowed a clearer association of ALCA and CLCA with the LCI. By contrast, the literature addresses the choice between attributional or consequential approaches depending on the question, i.e. its G&S. However, the text mining activity could have also proven that if the question involves a change in any way, as for CLCA, this will automatically affect the inventory by changing the system model, data gathering and approaches to solve multifunctionality issues. Similarly, text mining metadata associated "scenario-based" LCA with the goal and scope instead of LCI, as in the preliminary framework. Such approaches can be aimed at exploring different product options: such options are part of the question of the study, i.e., part of the goal of the analysis. In this sense, scenario-based LCA can also be seen as "prospective LCA". For these reasons, the authors suggest including it in the umbrella term of "explorative LCA".

Overall, the bottom-up data from the vast literature collection highlighted the novelty of some of the approaches presented. Explorative LCA and predictive approaches represent new trends and options for carrying out LCA analysis. Based on the few applications found, it seems clear that they aim to enable future-based analysis. The goal of such analyses is to assess emerging technologies and support environmentally aware decision-making during product development. Among others, they might present a high potential for further development and more frequent application. This is also due to the rise of machine learning and other tools for lifecycle data prediction.

Consistent with developments in LCA applications and novel approaches, the framework presented here can be easily adapted. As a main advantage, the framework and the classification refer to ISO standards and LCA fundamentals, i.e. the LCA Framework (International Organization for Standardization 2006a) and the algebraic calculations. This solution has been previously applied for defining classification systems in LCA uncertainties (Huijbregts 1998a) and proved to be sufficiently steady. In addition, the methodology used for the SLR and text mining is easily replicable. Such activities can be enhanced over time by integrating other filters or criteria for data selection, which can also be facilitated by informatics tools.

Lastly, with the enlargement of research papers' databases and text corpus to be processed, more automatic data selection and dictionary creation processes will be needed. Database enlargements can increase the robustness of results. However, more and more data control will be required. Extensive use of text data with insufficient quality could mislead the data mining process (Jugulum 2016), which means that intermediary text corpus selection will become a critical task. Moreover, for the analysis presented here, the creation of a dictionary, on the one hand, allowed for a more targeted multiwords selection, while on the other, creating a potential bias, which could lead the algorithm to further miss some context in the analysis. Such issues can be solved in the future by applying more complex processing models. Among them, the authors of this work draw attention to neural network algorithms, which could more automatically mimic the operations to recognise relationships between vast amounts of data and which have already been investigated and applied in the education sector (Okewu et al. 2021; Wu and Feng 2018). In conclusion, such instruments are expected to be increasingly integrated into research with the help of faster computational instruments while reducing manual effort and increasing accuracy.

Annex

This Annex includes the results of text mining (see Tables 4, 5, 6, 7, 8, 9, 10 and 11).

Table 4 Results text mining. Case attributional LCA

Rank	Collocation		Count	Attributed stage
1	attribut	consequenti	955	comparison approaches
2	attribut	model	327	LCI
3	attribut	impact	75	LCIA
4	ALCA	consequenti	55	comparison approaches
5	attribut	system	49	G&S
6	attribut	data	43	LCI
7	attribut	scenario	41	G&S
8	attribut	LCI	40	LCI
9	ALCA	model	37	LCI
10	attribut	process	29	G&S
11	ALCA	emiss	27	LCIA
12	attribut	inventori	25	LCI
13	alca	clca	23	comparison approaches
14	attribut	GHG	21	LCIA
15	attribut	process-bas	19	G&S
16	attribut	emiss	18	LCIA
17	ALCA	product	16	G&S
18	attribut	alloc	14	LCI
19	attribut	compar	14	G&S
20	attribut	weight	14	LCIA
21	ALCA	scenario	14	G&S
22	ALCA	system	14	G&S
23	attribut	materi	13	G&S
24	attribute-to-act	model	13	LCI
25	attribut	input	12	LCI
26	attributional-consequenti	distinct	12	comparison approaches
27	attribut	character	10	LCIA
Total			1930	

Table 5 Results text mining. Case consequential LCA

Rank	Collocation		Count	Attributed stage
1	consequenti	model	570	LCI
2	consequenti	attribut	184	comparison approaches
3	CLCA	ALCA	131	comparison approaches
4	CLCA	model	128	LCI
5	consequenti	LCI	99	LCI
6	consequenti	system	81	G&S
7	consequenti	databas	67	LCI
8	consequenti	scenario	55	G&S
9	consequenti	impact	46	LCIA
10	c-lca	model	34	LCI
11	CLCA	system	34	G&S
12	CLCA	aim	29	G&S
13	consequenti	greenhous	27	LCIA
14	consequenti	product	26	G&S
15	consequenti	data	24	LCI
16	consequenti	dataset	23	LCI
17	consequenti	process	22	G&S
18	CLCA	scenario	22	G&S
19	consequenti	GHG	21	LCIA
20	consequenti	inventori	20	LCI
21	CLCA	product	18	G&S
22	CLCA	attribut	16	comparison approaches
23	consequenti	character	15	LCIA
24	consequenti	prospect	14	comparison approaches
25	CLCA	compar	14	comparison approaches
26	consequenti	lcis	10	LCI
Total			1730	

Table 6 Results text mining. Case prospective LCA

Rank	Collocation		Count	Attributed stage
1	prospect	scenario	282	G&S
2	prospect	model	75	comparison approaches
3	prospect	technolog	66	G&S
4	prospect	consequenti	49	comparison approaches
5	early-stag	technolog	32	G&S
6	prospect	attribut	20	LCI
7	prospect	data	16	comparison approaches
8	exploratori	scenario	16	LCI
9	prospect	system	15	LCIA
10	prospect	futur	13	G&S
11	prospect	LCI	12	G&S
12	backcast	scenario	12	LCI
13	prospect	carbon	11	LCIA
14	prospect	assumpt	10	LCI
Total			629	

Table 7 Results text mining. Case retrospective LCA

Rank	Collocation		Count	Attributed stage
1	retrospect	prospect	53	comparison approaches
2	retrospect	data	16	LCI
3	tradit	attribut	19	comparison approaches
4	tradit	dynam	17	comparison approaches
5	tradit	emerg	12	comparison approaches
6	tradit	LCI	13	LCI
7	tradit	process	41	G&S
8	tradit	produc	10	G&S
9	tradit	product	49	G&S
10	tradit	static	22	comparison approaches
Total			252	

Table 8 Results text mining. Case scenario-based LCA

Rank	Collocation		Count	Attributed stage
1	scenario	scenario	1378	G&S
2	scenario	compar	479	comparison approaches
3	scenario	model	475	LCI
4	scenario	impact	408	LCIA
5	scenario	assum	375	LCI
6	scenario	uncertainti	209	G&S; LCI; LCIA
7	scenario	sensit	176	Interpretation
8	scenario	product	163	G&S
9	scenario	comparison	140	comparison approaches
10	scenario	data	124	LCI
11	scenario	produc	105	G&S
12	scenario	assumpt	100	LCI
13	scenario	technolog	98	G&S
14	scenario	emiss	97	LCIA
15	scenario	system	95	G&S
16	scenario	GWP	89	LCIA
17	scenario	process	84	G&S
18	scenario	explor	77	comparison approaches
19	scenario	carbon	76	LCIA
20	scenario	materi	63	G&S
21	scenario	GHG	62	LCIA
22	scenario	CO2	55	LCIA
23	scenario	LCI	52	LCI
24	scenario	dynam	51	comparison approaches
25	scenario	prospect	49	comparison approaches
26	scenario	databas	48	LCI
27	scenario	attribut	42	comparison approaches
Total			5170	

Table 9 Results text mining. Case dynamic LCA

Rank	Collocation		Count	Attributed stage
1	dynam	model	600	LCI
2	dynam	LCI	212	LCI
3	dynam	system	155	G&S
4	dynam	character	146	LCIA
5	dynam	inventori	135	LCI
6	dynam	impact	121	LCIA
7	dynam	weight	111	LCIA
8	dynam	materi	95	G&S
9	dynam	emiss	85	LCIA
10	dynam	carbon	83	LCIA
11	dynam	data	70	LCI
12	dynam	static	66	comparison approaches
13	dynam	process	64	G&S
14	dynam	scenario	62	G&S
15	dynam	GHG	58	LCIA
16	dynam	cfs	56	LCIA
17	dynam	GWP	56	LCIA
18	dynam	LCIA	54	LCIA
19	dynam	characterist	30	LCIA
20	dynam	CF	27	LCIA
21	dynam	greenhous	24	LCIA
22	dynam	hybrid	23	comparison approaches
23	dynam	product	18	G&S
24	dynam	prospect	18	comparison approaches
25	dynam	consequenti	17	comparison approaches
26	dynam	attribut	16	comparison approaches
27	dynam	wfs	15	LCIA
28	dynam	lcis	14	LCI
29	dynam	GWI	12	LCIA
30	dynam	technolog	12	G&S
31	dynam	characteris	11	LCIA
32	dynam	convent	11	comparison approaches
33	dynam	CO2	10	LCIA
34	dynam	futur	10	G&S
35	dynam	input	10	LCI
36	time-depend	cfs	31	LCIA
37	time-depend	character	31	LCIA
38	time-depend	model	18	LCI
39	time-depend	impact	13	LCIA
40	time-depend	inventori	12	LCI
Total			2612	

Table 10 Results text mining. Case static LCA

Rank	Collocation		Count	Attributed stage
1	static	dynam	221	comparison approaches
2	static	model	74	LCI
3	static	scenario	42	G&S
4	static	LCI	24	LCI
5	static	system	24	G&S
6	static	GHG	17	LCIA
7	static	cfs	16	LCIA
8	static	data	13	LCI
9	static	inventori	13	LCI
10	static	indic	12	LCIA
11	static	carbon	10	LCIA
12	static	character	10	LCIA
13	static	materi	10	G&S
14	static	versus	10	comparison approaches
Total			496	

Table 11 Results text mining. Case probabilistic LCA

Rank	Collocation		Count	Attributed stage
1	probabilist	model	103	LCI
2	probabilist	scenario	19	G&S
3	probabilist	uncertainti	12	G&S; LCI; LCIA
4	probabilist	character	11	LCIA
5	probabilist	input	11	LCI
6	probabilist	weight	10	LCIA
7	stochast	model	259	LCI
8	stochast	uncertainti	49	G&S; LCI; LCIA
9	stochast	weight	35	LCIA
10	stochast	process	28	G&S
11	stochast	epistem	18	comparison approaches
12	stochast	input	12	LCI
13	stochast	dynam	11	comparison approaches
14	stochast	compar	10	comparison approaches
Total			588	

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Data availability Complete datasets generated during the current study are made available from the corresponding author upon reasonable request.

Declarations

Conflict of interest The authors declare no competing interests.

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