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Review

How to Simplify Life Cycle Assessment for Industrial Applications—A Comprehensive Review

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Abstract: Life cycle assessment (LCA) has established itself as the dominant method for identifying the environmental impact of products or services. However, conducting an LCA is labor and time intensive (especially regarding data collection). This paper, therefore, aims to identify methods and tools that enhance the practicability of LCA, especially with regard to product complexity and variance. To this end, an initial literature review on the LCA of complex products was conducted to identify commonly cited barriers and potential solutions. The obtained information was used to derive search strategies for a subsequent comprehensive and systematic literature review of approaches that address the identified barriers and facilitate the LCA process. We identified five approaches to address the barriers of time and effort, complexity, and data intensity. These are the parametric approach, modular approach, automation, aggregation/grouping, and screening. For each, the concept as well as the associated advantages and disadvantages are described. Especially, the automated calculation of results as well as the automated generation of life cycle inventory (LCI) data exhibit great potential for simplification. We provide an overview of common LCA software and databases and evaluate the respective interfaces. As it was not considered in detail, further research should address options for automated data collection in production by utilizing sensors and intelligent interconnection of production infrastructure as well as the interpretation of the acquired data using artificial intelligence.

Keywords: life cycle assessment (LCA); parametric LCA; modular LCA; automation; aggregation; screening; simplification; manageable; review

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1. Introduction

Climate change has emerged as one of the greatest challenges to human development [1]. Given the increasing urgency to reduce global greenhouse gas emissions and the growing public awareness of climate change, transparency concerning environmental impacts is of great importance for decision-makers and companies, as it enables targeted optimization and the monitoring of potential progress. To ensure comparability and credibility for stakeholders, it is pivotal to have access to meaningful, replicable, transparent, and manageable methodologies [2,3]. One such metric is provided by life cycle assessment, which measures the environmental impact of products or services over their entire value chain, use and end-of-life phase and is expressed in various key figures of different impact categories (e.g., CO_2 and SO_2 equivalents) [4,5]. The most prominent standards for conducting LCAs of products are the Publicly Available Specification 2050 (PAS2050) [6], the GHG Protocol [7], as well as ISO 14067 [8]. These standards differ in terms of calculation and exclusion criteria [9] but are all based on ISO 14040 and ISO 14044 [10,11], which provide the principles, minimum requirements, and framework for life cycle assessments. Unlike LCA, the product carbon footprint (PCF) calculation is limited to the assessment of greenhouse gas emissions and thus focuses only on one impact category (global warming potential—GWP), which is why the PCF calculation method can also be considered as a limited or restricted LCA [4]. Compared to LCA, the PCF calculation is currently the focus of industry efforts owing to the strong public perception of greenhouse gas emissions and the fact that the carbon footprint has a much broader appeal than LCA itself [5]. Yet, for a holistic analysis of a product's environmental impact as well as to avoid problem-shifting, it is essential to consider other impact categories [5]. Focusing on GWP alone may present a misleading picture of environmental impacts, with other impact categories possibly being much more relevant [5,12]. This is especially relevant for comparative analyses, which intend to recommend a product with the lowest ecological impact. Moreover, once respective datasets are available, the calculation of other impact categories does not require additional effort when using LCA software.

LCA has become a mature and widely used method for assessing environmental impacts and is increasingly applied in the industrial sector. Nevertheless, several challenges are associated with its implementation, such as the time required for data collection and modeling, limited resources or data, lack of expertise, and the complexity of the product under consideration [13–15]. In response to these barriers, several methods to simplify LCAs have already been developed. The first overview of LCA simplification methods was provided by Weitz et al. [16] in 1995, who identified eight simplification categories based on discussions with LCA practitioners and researchers [16]. These methods comprise: 1. Limiting or eliminating life cycle stages, 2. Focusing on specific environmental impacts or problems, 3. Eliminating specific inventory parameters, 4. Limiting or eliminating impact assessment, 5. Using qualitative and quantitative data, 6. Using surrogate data, 7. Establishing criteria used as "showstoppers" or "knockouts", 8. Limiting the constituents studied to those that reach a certain quantity. In the same year, the U.S. Environmental Protection Agency (U.S. EPA) hosted a conference on LCA streamlining to promote the exchange of techniques and issues related to LCA simplification [17]. Following this, several other publications also addressed simplification methods but did not add any additional categories besides the ones already defined by Weitz et al. [18–21]. Coinciding with the debate on LCA simplification was the development of LCA standards, and the first international standard for LCA was published by the International Standards Organization (ISO) in 1997 [21,22]. Since then, LCA has evolved into a mature methodology and simplification approaches have been widely used and are now part of everyday LCA practice. These include, for instance, limiting system boundaries, setting cut-off values, or using LCA software. Nevertheless, there have been few updates on the research and development of simplification methods until recent reviews by Beemsterboer et al. [23] and Gradin and Björklund [21]. Both reviews systematize LCA simplification methods, incorporate previously defined approaches and add new categories. New categories identified by Beemsterboer et al. [23] include the use of methodological standards, guidelines, and standardized LCA tools, computational LCA using LCA software, and automated data integration [23]. Gradin and Björklund [21] likewise added the category tool/database, which refers to the use of LCA software, as well as the category comparative LCA with the omission of identical elements and screening LCA [21]. Overall, several simplification methods exist that are widely used to overcome the obstacles associated with LCA. Yet, the assessment of very complex products or product portfolios consisting of many components remains a major difficulty, even when the existing simplification methods are applied. This is because most of the existing approaches are related to modifying the LCA methodology rather than facilitating the assessment procedure. Since the modeling of complex products or large product portfolios often requires a large amount of data, and most of the existing simplification methods do not aim to facilitate data collection and processing, LCA of these types of products remains a challenging endeavor. Considering this, the purpose of this review is to identify approaches that facilitate the LCA process with special regard to product complexity and variance and make them more applicable by identifying suitable methods and tools. In this paper, we therefore conducted a systematic literature review in order to answer the following research questions:

- Which approaches exist to increase the practicability of the LCA calculation of complex products and product portfolios consisting of a large number of components?
- How can these simplification approaches be categorized and what is their respective benefit for the LCA calculation?
- Which tools are available that can facilitate the assessment?

2. Methodology

The research methodology described in this paper can be divided into four parts. The starting point was a preliminary literature search aimed at identifying the barriers to performing LCA calculations of products with a focus on complex products. Based on this, it was possible to define targeted search categories for the subsequent systematic literature review. The search results were then analyzed to identify suitable approaches to improve the manageability of LCA. This process is illustrated in Figure 1.

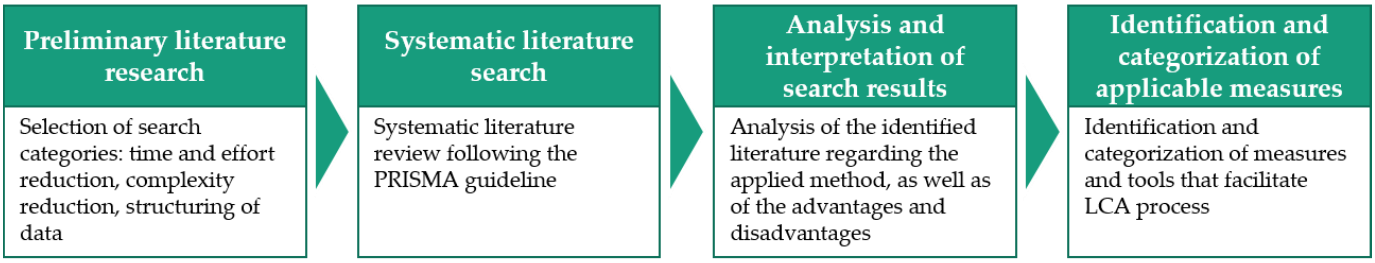

Figure 1. Research process.

2.1. Selection of Search Categories

For the preliminary literature search, the Scopus database and Google were queried using a combination of various terms related to LCA, complex products, and simplification. The term complex products is used to refer to products that are composed of a large number of individual parts and therefore have a very extensive bill of materials (BOM). The resulting selection of scientific publications was then analyzed regarding the barriers associated with carrying out LCAs, in particular LCAs of complex products. The identified barriers were used to define search strings for the main literature search that took into account the specifics related to the LCAs of complex products. Consequently, the search strategy for the main literature search was not limited to approaches that were declared as simplification approaches, especially since these are not always recognized as such. The inclusion of barriers in the search string allowed a broader range of approaches to be identified. The most frequently stated barrier is time and resource requirement [24–27], which can mostly be attributed to the life cycle inventory phase, which is very data intensive. Data collection is considered to be the most time and therefore cost-intensive element of LCA [21,25,28,29]. In addition, the complexity of the product being assessed, data and resource constraints, as well as the required expert knowledge were frequently mentioned challenges [23,30–32]. For complex products such as vehicles [33], aircraft [34], buildings [28,31,32], or capital goods [35,36] that consist of a large number of different components and materials, the high effort required to prepare and categorize the data is particularly critical. Consequently, modeling all parts and materials is often not feasible [34]. Moreover, for products with an extensive bill of materials, the number of components that are purchased from suppliers generally increases. For these components, primary data are often not available and generic databases have to be used. Yet, especially for very specific components, the databases usually do not contain the required data. In addition, some users, especially in industry, consider the LCA methodology to be too complex to be used routinely [37]. Consequently, industrial scaling of LCA requires simplification and approaches that increase the application efficiency of the underlying methodology [38].

Aiming to address the most frequently stated barriers, the following three search categories were defined to serve as the basis for the systematic literature review: "effort reduction", "complexity reduction" and "structuring of data" (compare Figure 2).

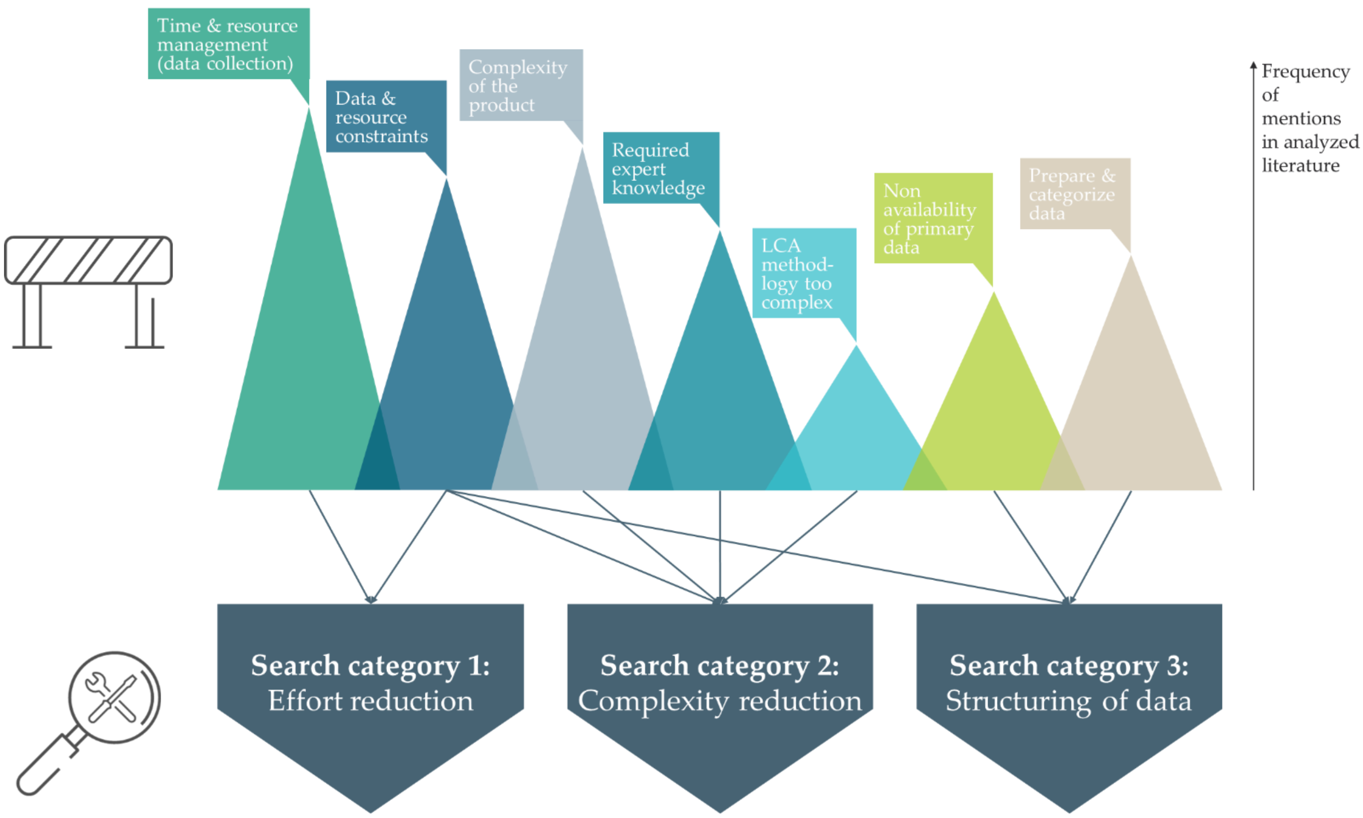

Figure 2. Derivation of search categories from barriers stated in literature.

2.2. Literature Review

The following systematic literature search is based on the PRISMA statement protocol (preferred reporting items for systematic reviews and meta-analyses), which served as a guideline for ensuring transparency, completeness, and accuracy [39,40]. For the identification of relevant studies, three search strings were defined, each representing one of the previously defined categories, namely "time and effort reduction", "complexity reduction" and "structuring of data" (Figure 3). For each search string, the field code "TITLE-ABS-KEY" (returns documents where the search terms appear in the title, abstract, or keywords) was used and various LCA terms were combined with the corresponding terms of the search categories. The search was conducted in March 2022 using the Scopus database; studies in English and German languages were included. Furthermore, no time restrictions concerning the date of publication were applied. As illustrated in Figure 3, the proximity operator W/10 was used instead of the boolean operator AND, meaning that the terms in the query should not be more than 10 words apart from each other. The underlying intention was to increase the probability of identifying records for which the defined terms are in thematic relation to each other. An initial search using the AND operator returned more than 6400 records, many of which, however, proved to be irrelevant after initial screening. Consequently, the search strategy was adjusted as described above.

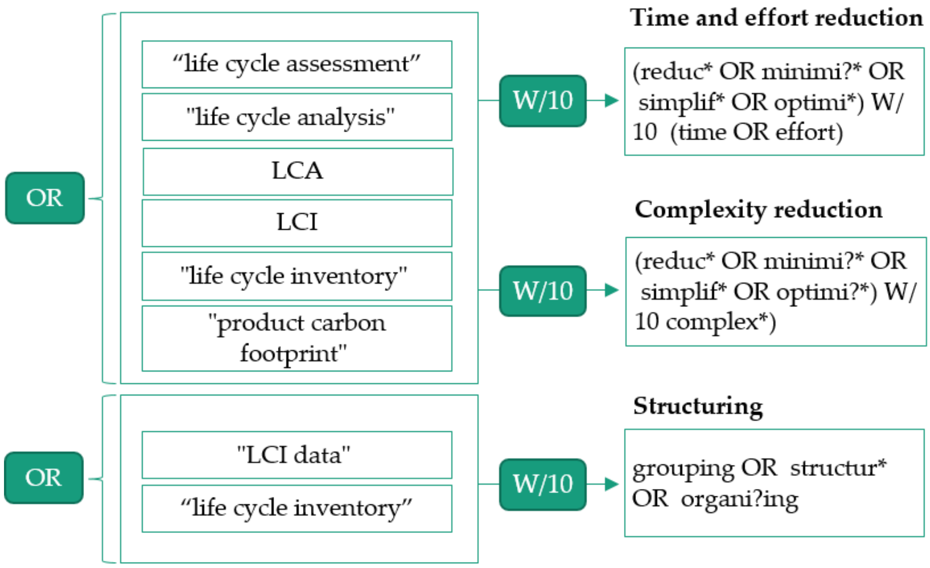

Figure 3. Overview of the search strings used for the systematic literature review, * and ? represent wildcards that can be used when a word has multiple spelling or ending variations.

Overall, the Scopus database search identified 172 records, and an additional 33 documents were identified via other methods, e.g., snowballing (searching for cited and citing studies) or Google search (Figure 4). Duplicates were then removed, and the titles and abstracts of the identified papers were screened. During this step, 70 documents were excluded as they focused on other subjects that are not related to LCA, like measurements of lung ventilation (lung clearance index—LCI) or algorithms for solving optimization problems. In the next step, all studies were assessed for eligibility. Studies that did not address at least one of the identified barriers were excluded. At the end of the PRISMA process, 76 studies were classified as relevant and consequently included in the following detailed analysis (compare Figure 4).

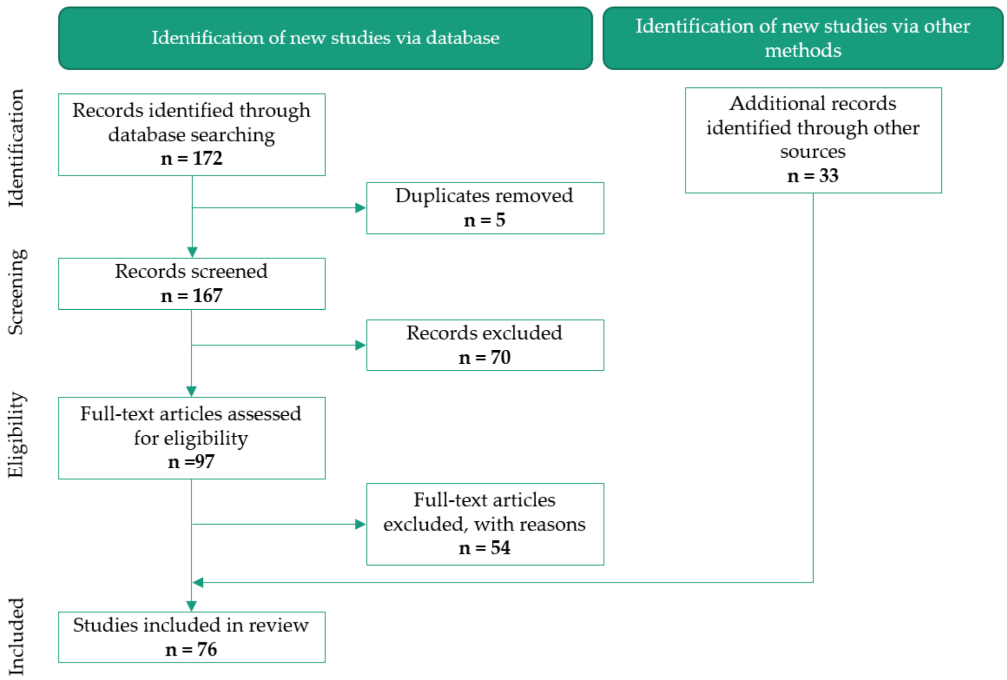

Figure 4. PRISMA flowchart.

2.3. Analysis of the Search Results

Subsequently, the included publications were analyzed for the approach that was used or described for conducting the LCA and its respective advantages and disadvantages. This allowed the identification and categorization of measures/procedures that facilitate the LCA process. To this end, the simplification that was applied was first identified and documented for each study and then grouped based on commonalities to define respective categories. The decisive factor for the assignment to categories was that at least one of the identified barriers, namely, time, effort, and complexity was addressed through the respective approach.

3. Results

The 76 research papers were first analyzed for the applied simplification and then grouped into categories of studies that applied the same or similar approaches. A category was created when the number of studies applying the same or similar approach was equal to or larger than five. Thereby, the following categories were identified (Figure 5).

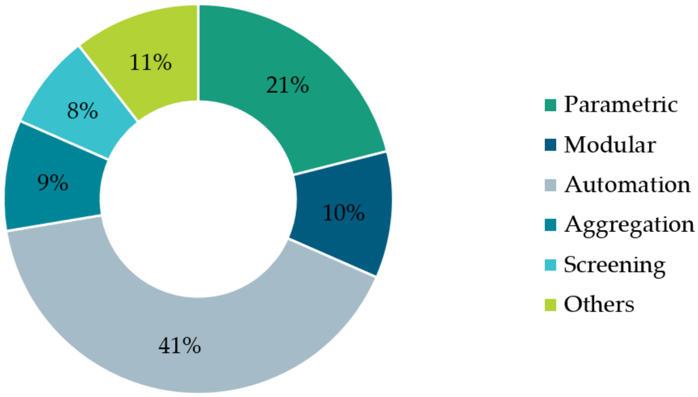

Figure 5. Identified categories, based on the systematic literature review. The percentage refers to the category's share of the total included studies.

For each of the defined simplification categories, Figure 6 illustrates the addressed barriers (compare Section 2.1). Furthermore, it was visualized in which phase(s) of an LCA the individual simplification methods could be applied. The authors state that simplification methods for the final interpretation stage of LCAs might exist. However, the extensive literature search described in this article showed no results in this respect.

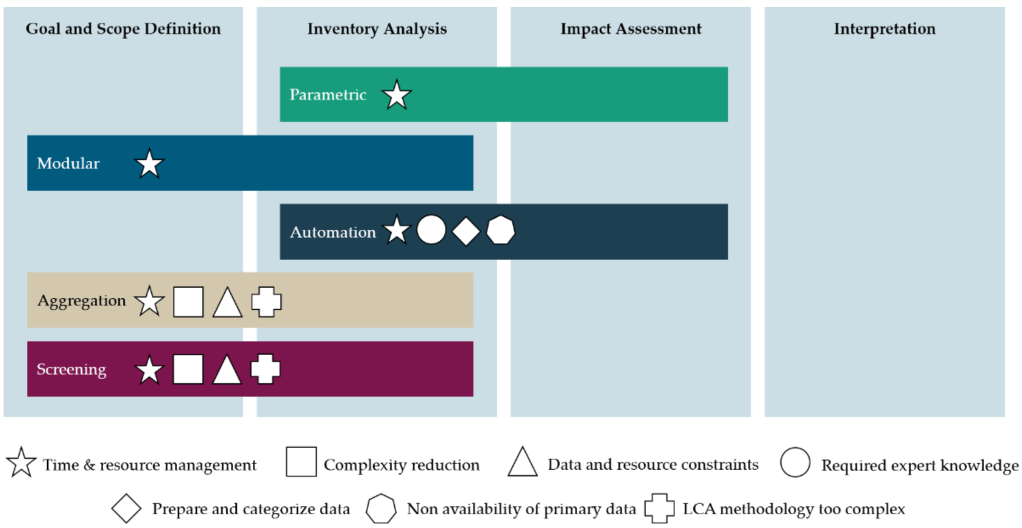

Figure 6. Addressed barriers and phases of LCA (as defined in ISO 14040) per simplification category.

3.1. Parametric LCA

The parametric approach is used to link the LCI to process or product-related parameters or to present the final LCA results directly as a function of such [41–43]. This simplifies the conduction of scenario analyses, as the defined parameters can easily be varied (Table 1). Hollberg and Ruth [44] applied parameterization to the life cycle assessment of buildings. Geometry, materials, building services, and boundary conditions were defined parametrically, and environmental impacts were calculated based on these input parameters. Niero et al. [42] evaluated the use of parameters in the context of LCI in the wood pallet sector. Their parametric LCI model is suitable for calculating the LCI for a range of products that have similar characteristics. Mueller et al. [45] parameterized the LCI using design parameters, thereby enabling LCA at the design stage. Kamalakkannan and Kulatunga [46] likewise proposed a parameterized LCA model that could be used for eco-design optimization and decision-making in the early design phase. Cooper et al. [41] examined parameterization methods in the European Reference Life Cycle Data System (ELCD), ecoinvent v3, and the U.S. Department of Agriculture's Digital Commons, identifying seventeen categories of parameters (raw data and formulas). When parameterizing the results, it is necessary to determine a correlation between the environmental hotspots and the most important parameters, such as resource inputs, parameters for physical or thermodynamic properties, or process parameters. For this purpose, the environmental hotspots are usually identified as a first step, then a correlation is determined and an equation for estimating the environmental impacts is derived. This is often carried out through regression analysis. Kuo et al. [47] developed a parametric tool to estimate the environmental impact of semiconductor packaging technologies based on regression analysis. Two regression equations were defined to evaluate the environmental impacts of gold and copper wire based on wire mass and packaging volume. Huang et al. [48] similarly, developed a parametric tool that is based on a regression analysis, to analyze the environmental impact of semiconductors. They performed carbon footprint calculations for the manufacturing of 7,114 products based on six parameters, namely function type, generation, technology node, mask layer, metal layer, and poly layer. Lee and Thomas [49] evaluated the environmental impact of electric medium-duty trucks under varying operating conditions using a parametric LCA and compared the results to those of non-electric technologies on the basis of physical simulations. Abyar et al. [50] conducted the sensitivity analysis of their LCA of a biological phosphorus removal system by defining a mathematical function dependent on various parameters that were identified to have relevant impact on the overall ecological impact of the system.

Table 1. Advantages and disadvantages of the category parametric LCA, distinguished in the parameterization of LCA results and the parameterization of LCI data.

Advantages	Disadvantages
Parameterization of LCA results	
• Time and cost savings due to a reduced effort when calculating the LCA results of product variations.	• The parametrization only provides aggregated results; a detailed analysis on a process or input/output level is not possible. • The effort to determine the parameterized equations might be high. • Only applicable to one impact category, as the parameterization is impact-specific.
Parameterization of LCI data	
• Time and cost savings when conducting scenario analyses. • Parameters can easily be changed; permits the automated generation of variants (this also enhances the interpretation). • No expert knowledge is required, once the parameters are defined. • Can be used in the early design process. • Suitable for products that have similar characteristics, e.g., mass customization, large product portfolios.	• The effort to determine the parameterized equations might be high.

3.2. Modular LCA

The modular approach refers to the modeling of product systems based on transferable elements that can be reused for other studies and calculations [30,51–53], therefore saving time and costs for the modelling (Table 2). The aim is to make reuse as simple and effective as possible [30]. Usually, the LCA of each module is calculated separately. Subsequently, the individual modules are aggregated to obtain the result for the whole system [52]. Steubing et al. [51] proposed a modular LCA approach to optimize the scenario analysis and the selection of key decisions along the value chain. For this purpose, the value chain of the assessed product (heat, at consumer) was divided into modules that can be linked in different ways. Module dependencies are shown in a matrix and individual modules are substitutable once they generate identical outputs. Similarly, Black et al. [54] used interchangeable modules to evaluate alternative biofuel supply chains. The modular approach enables the examination of data sensitivity or changes in practice (e.g., differences in feedstock production or process practices). Christensen and Wiezorek [55], on the other hand, applied a modular approach to evaluate different product variants of products that share similar characteristics, namely mass customization (MC) products. Since MC is based on the principle of modularity, the evaluation of each building block (module) was proposed, to derive the LCA of the superordinate system from the combination of the modules. For the implementation, the authors proposed a system architecture that integrates ERP data and sustainability data into a product configurator. The product configuration can be selected in the configurator software and the LCA results are calculated accordingly. Due to the linkage with ERP and sustainability data, it could be assumed that the model is transferable to newer materials and production processes, although this was not further specified. Groetsch et al. [53] developed a modular LCA concept that aimed to optimize the production of carbon fibers by investigating different scenarios, alternative precursor materials, different types of carbon fiber, and varying the production parameters. The model consists of reusable modules based on core production processes for which process and material parameters can be varied easily. In addition, the proposed modeling concept enables the combination of LCA and life cycle costing (LCC) and is intended to be used in the early stages of development. In the approach proposed by Rebitzer [30], the same steps were followed as in a conventional LCA, but the impact assessment, classification, and characterization steps were performed after aggregating the relevant inventory data at the process level rather than at the system level. Buxmann et al. [56] applied the same concept as proposed by Rebitzer [30]. Orzechowski and Mrozik [57] evaluated the environmental impact of different Volkswagen Golf vehicle models, over the period of 30 years, based on the structural data of a vehicle. Therefore, the structure of the vehicle was divided into five systems corresponding to basic functional systems. This structure was then further divided into units consisting of specific masses of different materials.

Table 2. Advantages and disadvantages of the modular LCA.

Advantages	Disadvantages
• Time and cost savings, as modules can be reused; when making changes to an existing product, not the entire LCA model has to be changed. • Allows the comparison of alternative value chains. • Models can be used by non-LCA experts.	• When comparing products from different eras, inconsistent LCI data is used, this means datasets with different actuality are mixed, if they are not constantly updated, which in turn is labor intensive.

3.3. Automation

The automation category refers to the automation of certain parts of the LCA, such as the automated calculation of results or the LCI generation via automated data integration [15,58–60]. The automatic calculation of results describes the basic function of LCA software and is therefore not discussed further, as software tools and databases are addressed in Section 3.3.1. The automatic generation of LCI data can be achieved through different approaches and generally utilizes interfaces between LCA software and other software, such as an enterprise resource planning (ERP) system, to obtain the required data. So far, three different interface methods have been discussed in the literature, which differ in terms of their level of integration. These link the LCA software to a database or the ERP system, adapting the complete LCA functionality into the ERP system, and add the life cycle impact assessment (LCIA) part from the LCA into the ERP system [58,61,62]. The motivation for automation is to reduce the time and effort required to collect and process LCI data (Table 3). Koffler et al. [15] described a method developed by Volkswagen to automate parts of a vehicle's LCI. Automation was shown to significantly reduce the time and labor required to produce a vehicle's LCI, resulting in an 80 % efficiency gain. Moreover, several studies exist that focus on linking product and process information with LCA data and software. Rovelli et al. [63] proposed a general methodology for developing a modular tool that integrates spreadsheets, LCA software, coding, and visualization modules that can be modified independently. Zhou and Tao [64] proposed a conceptual framework for integrating enterprise software tools, databases, and LCA to address the complexity of inventory analysis. Ferrari et al. [65] described the architecture and application of a dynamic LCA system that integrates the ERP system with a customized LCA tool. Wehner et al. [66] proposed a workflow automation concept, the Sustainability Data Science Life Cycle (S-DSLC) concept. The LCA methodology is combined with the standard process for data mining (CRISP-DM) and the Data Science Life Cycle (DSLC). The concept is implemented in the KNIME Analytics Platform [67]. The model is based on ERP and LCA data, which are automatically transformed into a standardized format to enable the calculation of the environmental impact. Using a use case that examines the sustainability of the procurement process for semi-finished steel products, it was shown that the concept offers significant scalability improvements for handling large product portfolios. In the field of LCA of buildings, there were several options to link the building information model (BIM) with LCA software. Tally, for instance, is a plugin for the planning software Revit that allows information about building materials to be entered into the software and quantifies environmental impacts based on that information [68,69]. In addition, several interface tools have been developed to link BIM with LCA software and automatically extract relevant LCI data from the BIM [70–74]. Teng et al. [75] provided a comprehensive review on BIM-integrated LCA as described in the literature. Lu et al. [76] not only focused on the simplification of LCA, but also on LCC by the utilization of BIM. Both publications identified the extraction of material data from BIM software, as well as the respective integration in external (LCA-) software as relevant methods. Furthermore, plug-ins for the BIM software [75] and the inclusion of economic and ecologic information in the BIM software were mentioned [76]. In contrast to BIM integration, the automated integration of BOMs has been less widespread in other industries, which seem to be lagging behind the construction industry. Yet, as shown in Table 4, software options to link product and process data from ERP software tools and spreadsheet-based software with LCA software exist.

Table 3. Advantages and disadvantages of automation in LCA.

Advantages	Disadvantages
• Time and cost savings → LCI data collection effort is reduced. • No/reduced manual data entry required → errors are minimized. • Improvement of results and granularity. • No LCA experts are required to conduct the LCA.	• Potential interoperability issues between the LCA software and the ERP system or a database. • Setting up the automation solution might be initially labor intensive.

For the computer-aided calculation of LCA, LCA software and databases are required. LCA software solutions support the LCI and LCIA phases by collecting relevant inputs and outputs and subsequently converting them into environmental impacts. Databases form the basis for modeling background data [77]. The increasing importance of the computational calculation of LCA using LCA software can be observed from the number of publications combining the terms "LCA" and "computational", which has grown almost exponentially during the past years (Figure 7). Computational calculation using tools and databases is state-of-the-art and is widely used nowadays [77].

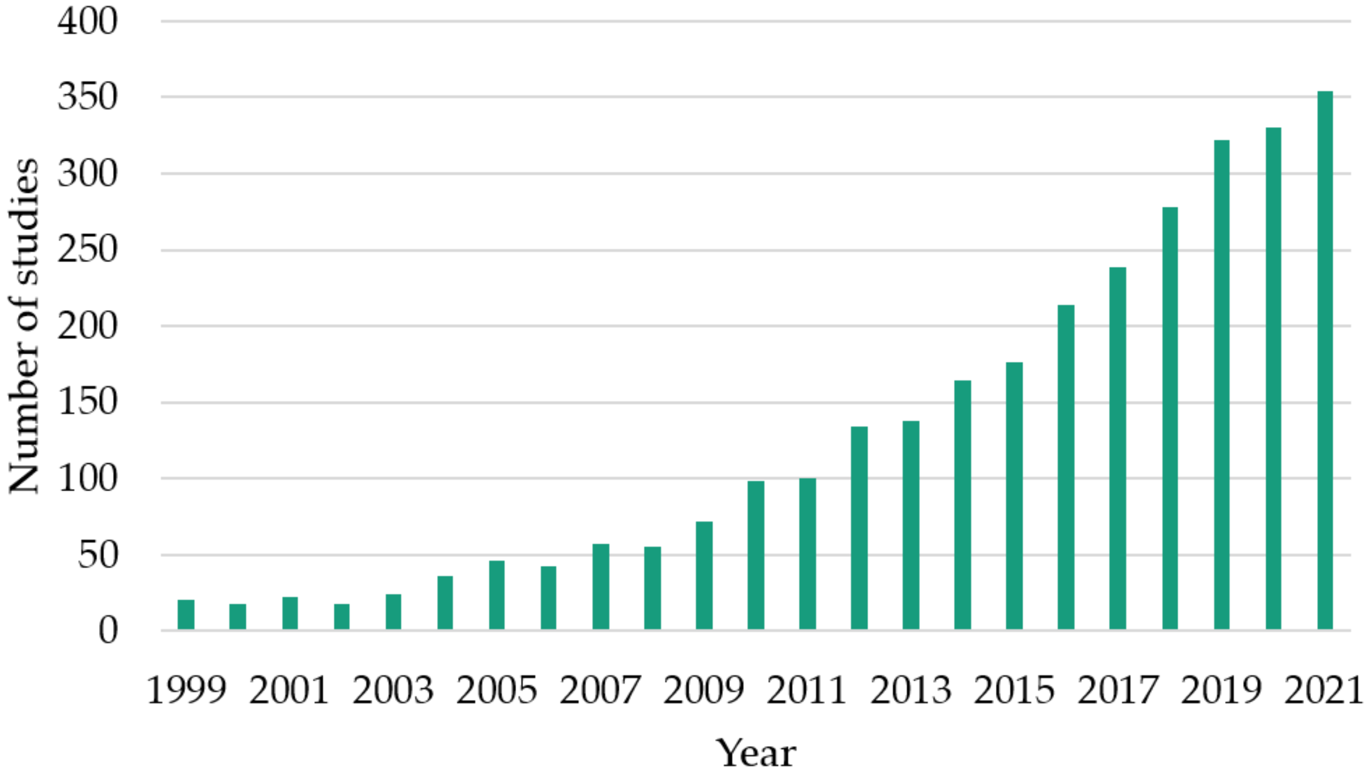

Figure 7. Number of articles containing terms "life cycle assessment" or LCA and computational since 1999.

Table 4. Overview of generic LCA and PCF tools.

Type	Software/Tool	Interface Methods		Provider	
		LCA software and ERP system/spread sheet software	LCA functionality in the ERP system		
LCA software	GaBi	x		Sphera	[78]
LCA software add-on	GaBi DfX	x		Sphera	[79]
LCA software add-on	GaBi Envision	x		Sphera	[80]
LCA software	SimaPro	x		PRé Sustainability	[81]
LCA software add-on	SimaPro API	x		PRé Sustainability	[81]

Table 4. *Cont.*

Type	Software/Tool	Interface Methods		Provider	
		LCA software and ERP system/spread sheet software	LCA functionality in the ERP system		
LCA software	Umberto 11	x		iPoint-systems gmbh	[82]
LCA software	OpenLCA	x		GreenDelta GmbH	[83]
LCA software	LCA Calculator			LCA Calculator Ltd.	[84]
LCA software	SULCA			VTT Technical Research Centre of Finland LTD	[85]
LCA software	iPoint	x		iPoint	[86]
Carbon footprint calculator	iPoint Product Sustainability	x		iPoint	[87]
Carbon footprint calculator	Calculation tools—Greenhouse gas protocol			World Resource Institute, World Business Council for Sustainable Development	[88]
ERP system	Sustainability Management Initiative System		x	Samsung SDI	[89]
LCA software	Ecochain			Ecochain Technologies BV	[90]
LCA software	Brightway2	x		Sphinx 4.5.9 & Alabaster 0.7.12	[91]
LCA software	CMLCA			Universiteit Leiden	[92]
LCA software	Ecospeed			Ecospeed	[93]
Carbon footprint calculator	SiGreen		x	Siemens	[94]
Carbon footprint calculator	SAP Product Carbon Footprint Analytics		x	SAP	[95]
Carbon footprint calculator	Carbmee		x	Carbmee GmbH	[96]
LCA software	CCalc			University of Manchester	[97]
Carbon footprint calculator	Sinai			Sinai Technologies	[98]
LCA software	GEMIS (Globales Emissions-Modell integrierter Systeme)			IINAS (Internationales Institut für Nachhaltigkeits analysen und -strategien)	[80]

3.3.1. LCA Software

The use of LCA software is nowadays state-of-the-art, and numerous software tools are available and new ones are continuously being developed. Software tools that are suitable for generic assessments, i.e., not tailored to a specific application, are listed in Table 4. In addition to the name of the software/tool and the provider, Table 4 also contains information about the type of software and the level of integration. In terms of the software type, four categories are distinguished, namely "LCA software", "LCA software add-on", "Carbon footprint calculator" and "ERP system". The first two categories refer to common LCA software and add-ons to these, i.e., extensions to the LCA software. Carbon footprint calculators refer to tools that only calculate the carbon footprint and do not focus on other impact categories. The category "ERP system" refers to an enterprise resource planning system with integrated sustainability data. The interface methods are divided into two integration levels, namely "LCA software and ERP system/spreadsheet software interface" and "LCA functionality in ERP system". These levels were selected in agreement with those already described in Section 3.3, whereas the adaptation of the complete LCA functionality into the ERP system and the addition of the LCIA part from the LCA into the ERP system are combined into one integration level. For the software for which no "x" is set, no interface to other programs exists.

Table 5 lists the main advantages and disadvantages of using LCA software.

Table 5. Advantages and disadvantages of using LCA software.

Advantages	Disadvantages
• The use of LCA software allows for a standardized procedure. • LCA software offers a direct connection to LCI databases. • Depending on the software, visualization of results is possible, which aids interpretation.	• Software training is required. • License fees may apply.

3.3.2. LCI Databases

LCI databases contain LCI data on a product or process in- and outputs and the corresponding material, energy and emission flows. LCI databases are generally used when primary data is not available, as is mostly the case for upstream and downstream processes. While the use of LCI databases allows for a reduction in effort during data collection, the selection of suitable datasets is a labor-intensive task. Since the emergence of the first LCI databases in the 1990s [22], numerous datasets have been created by various providers in a variety of sectors and regions, some for free and some for purchase. This diversity makes it difficult to maintain an overview and select appropriate datasets. Table 6 therefore, provides an overview of common LCI databases, as well as of input-output databases and databases for social LCA. The compilation does not claim to be complete. It is expected that especially countries of the Asian continent provide datasets that were not identified due to the language barrier.The input-output (IO) analysis is a form of macroeconomic analysis, which is increasingly used in combination with LCA [22,99]. Economic IO tables provide information regarding the value of economic transactions between sectors in an economy [100]. This data can be extended with environmental information, such as emissions or primary resource use, as well as with information regarding social aspects [100]. In the IO-based LCA inventory, data are collected at the macroeconomic level, assigned to specific industries, and subsequently, the direct impacts are aggregated into the impacts for each good or service produced using economic allocations [22]. The main advantage is that a quick and comprehensive assessment is possible, which is why this approach is often also used as a screening tool. In addition, IO data can be utilized to fill data gaps in process LCAs via consumption-based calculations and to assess economic and social sustainability [22]. However, the depth of the analysis depends on the statistics that are used as a basis; the data are often several years old, and only a limited number of environmental impact categories are covered [22,99]. Social LCA databases contain data on social impacts in terms of sectors and countries [22].

Table 6. LCI databases, input/output databases as well as databases for social LCA; not exhaustive.

Database	Sector	Number of Datasets	Geography	Free/For Purchase	Provider	
			LCI database			
Ecoinvent	Generic	18,000+	Worldwide	For purchase	Ecoinvent	[101]
GaBi	Generic	15,000+	Worldwide	For purchase	Sphera	[102]
EstiMol	Chemicals	~14,000	Worldwide	Free	Ifu Hamburg GmbH	[103]
Field Crop Production	Agriculture	12,000+	US	Free	University of Washington Design for Environment Laboratory	[104]
Carbon minds	Chemicals, plastics	10,000+	Worldwide	For purchase	Carbon Minds	[105]
MTU Asphalt Pavement Framework	Construction	8000+	US	Free	Federal Highway Administration	[104]

Table 6. *Cont.*

Database	Sector	Number of Datasets	Geography	Free/For Purchase	Provider	
ProBas	Generic	8000+	Worldwide	Free (ProBas+ for purchase)	German Federal Environment Agency (Umweltbundesamt)	[106]
US LCI Public	Generic	6000+	US	Free	National Renewable Energy Laboratory	[104]
UVEK LCI data	Construction	~5000	Switzerland	Free (Ecoinvent license required)	KBOB, Ecobau, IPB	[107]
Agri-footprint	Agriculture, food	~4000	Worldwide	For purchase	Blonk Sustainability	[108]
Inventory Database for Environmental Analysis (IDEA)	Generic	~3800	Japan	For purchase	AIST, JEMAI	[109]
US electricity baseline	Energy	3000+	US	Free	Federal LCA Commons	[104]
Environmental Footprint data	Generic	3000+	Worldwide	Free	European Commission	[110]
Agribalyse	Agriculture, food	~2700	France	Free	Argibalyse	[111]
Swine, poultry, beef production	Animal husbandry	2500+	US	Free	University of Arkansas	[104]
World Food LCA database	Agriculture, food	~2300	Worldwide	Free	Quantis	[112]
ESU World Food	Agriculture, food	~2000	Worldwide	For purchase	ESU services Ltd.	[113]
Industrial Design & Engineering MATerials database (IDEMAT)	Generic	~1800	Worldwide	For purchase	Gruner-Team Sustainability	[114]
Ökobaudat	Construction	1500+	Germany (Worldwide)	Free	German Federal Ministry of Transport, Building and Urban Development	[115]
Construction and Demolition Debris (CDD) Management	Construction	900+	US	Free	United States Environmental Protection Agency	[104]
Evah OzLCI2019	Generic	900+	Australia	Free	The Evah Institute	[114]
WEEE LCI database	Waste	900+	Worldwide	Free	Ecosystem	[116]
Datasmart LCI	Textiles, packaging	700+	US	For purchase (for SimaPro users)	Long Trail Sustainability	[117]
CPM Database	Generic	~700	Sweden, Europe, Worldwide	Free	Centre For Environmental Assessment of Product and Material Systems Chalmers University of Technology	[118]
Swiss Agricultural Life Cycle Assessment database (SALCA)	Agriculture	~700	Switzerland	For purchase (for SimaPro users)	Agroscope	[119]
Australian National Life Cycle Inventory Database (AusLCI)	Generic	600+	Australia	For purchase	Australian Life Cycle Assessment Society (ALCAS)	[120]
Coal extraction	Coal	600+	US	Free	National Energy Technology Laboratory	[104]
Chinese Life Cycle Database (CLCD)	Generic	~600	China	Free (for eBalance users)	Sichuan University, China; IKE Environmental Technology Co., Ltd., China	[121]

Table 6. *Cont.*

Database	Sector	Number of Datasets	Geography	Free/For Purchase	Provider	
Forestry and forest products	Forestry	500+	US	Free	CORRIM	[104]
The Evah pigments database	Pigments	190+	Worldwide	For purchase	The Evah Institute	[114]
BioEnergieDat	Bioenergy	170+	Germany	Free	German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety	[114]
Heavy Equipment Operation	Construction	160+	US	Free	United States Environmental Protection Agency	[104]
Aviation Fuel	Fuel	120+	US	Free	University of Washington Biofuels and Bioproducts Laboratory	[104]
Kraft pulp	Food	100+	US	Free	NC State Department of Forest Biomaterials	[104]
Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET)	Vehicles, energy carrier	~80	US	Free	U.S. Department of Energy, Argonne National Laboratory	[122]
Woody biomass	Forestry	70+	US	Free	US Forest Service Forest Products Laboratory	[104]
Plastics Europe	Plastics	50+	Worldwide	Free	Plastics Europe	[123]
Athena Life Cycle Inventory Product Databases	Construction	~50	US, Canada	Free	Athena Sustainable Materials Institute	[124]
Worldsteel	Steel	35+	Worldwide	Free	World Steel Association	[125]
ERASM SLE	Surfactants	30+	Worldwide	Free	ERASM	[126]
Canadian Raw Material Database (CRMD)	Commodity materials	18	Canada	Free	University of Waterloo	[127]
Input-output database						
EXIOBASE	Generic	Not applicable	Worldwide	Free	EXIOBASE Consortium	[128]
US Environmentally Extended Input-Output (USEEIO)	Generic	Not applicable	US	Free	United States Environmental Protection Agency	[104]
Carnegie Mellon: EIO-LCA	Generic	Not applicable	US, Germany, Spain, Canada, China	Free	Carnegie Mellon University	[129]
3EID	Generic	Not applicable	Japan	Free	Center for Global Environmental Research, National Institute for Environmental Studies	[130]
OPEN IO-Canada	Generic	Not applicable	Canada	Free	CIRAIG	[131]
CEDA Factors	Generic	Not applicable	US	For purchase	VitalMetrics Group	[132]
EORA Global Supply Chain Database	Generic	Not applicable	Worldwide	For purchase	KGM & Associates Pty. Ltd.	[133]
Global Trade Analysis Project (GTAP)	Generic	Not applicable	Worldwide	For purchase (older versions are free)	Purdue University	[134]

Table 6. *Cont.*

Database	Sector	Number of Datasets	Geography	Free/For Purchase	Provider	
MRIO-Global Footprint Network	Generic	Not applicable	Worldwide	For purchase	Global Footprint Network	[135]
Inter-Country Input-Output (ICIO) Tables	Generic	Not applicable	Worldwide	Free	Organisation for Economic Co-operation and Development	
ADB MRIO	Generic	Not applicable	Asia	Free	Asian Development Bank	[136]
Databases for social LCA						
Product Social Impact Life Cycle Assessment database (PSILCA)	Generic	14,000+	Worldwide	For purchase	GreenDelta GmbH	[137]
Social Hotspots Database (SHDB)	Generic	7900+	Worldwide	For purchase	NewEarth B	[138]

Figure 8 illustrates the share of datasets that are accessible free of charge compared to the fee-based datasets. "Under condition" in this context means that the users need active licenses for LCA software (SimaPro) or other databases (Ecoinvent).

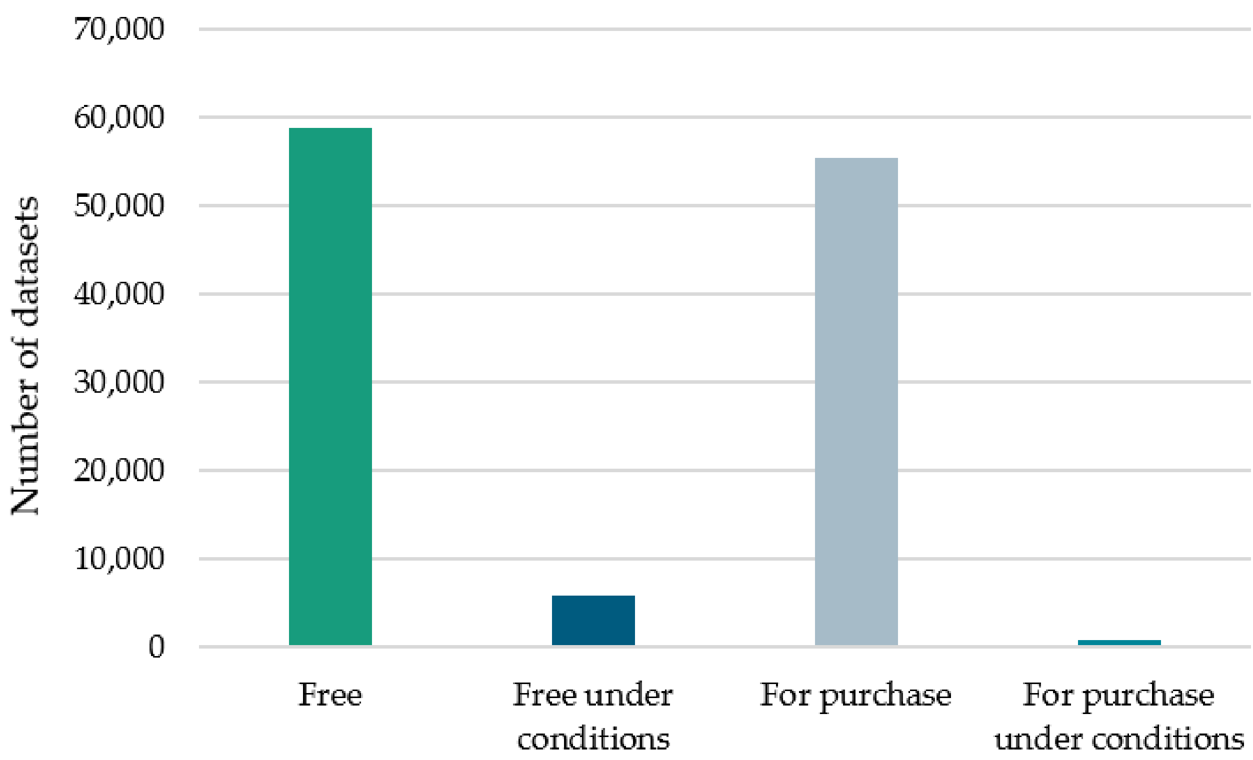

Figure 8. Access to available datasets.

Figure 9 visualizes the availability of datasets per sector and country. The diameter of the circular diagrams depicts the number of datasets in relation to the number on the global level (61,815).

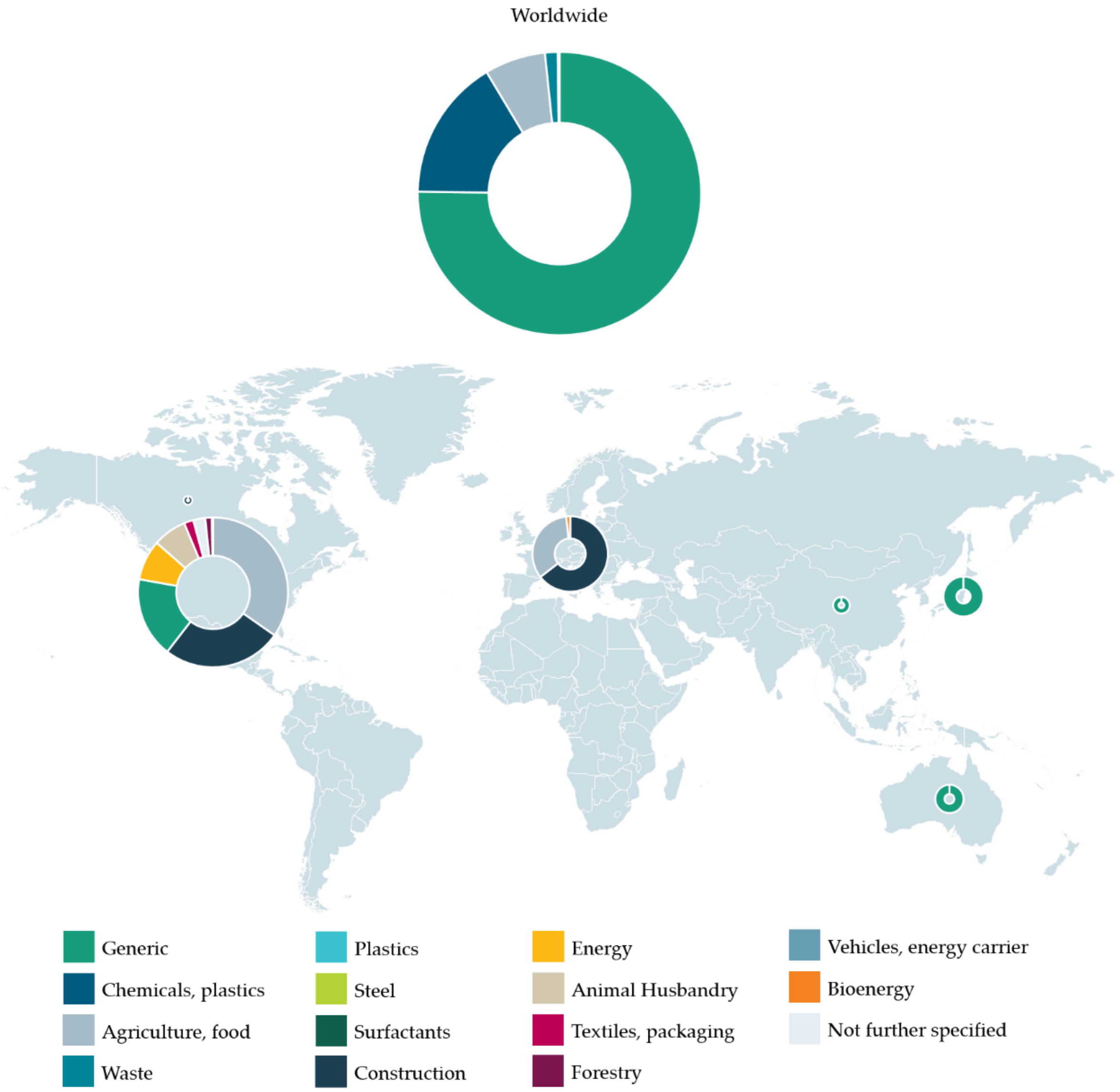

Figure 9. Availability of LCI datasets per country and sector.

The use of LCI data from multiple databases offers the opportunity to increase data availability. At the same time, LCI data interoperability, i.e., the ability to seamlessly integrate datasets, poses a challenge to linking LCI data from different sources (Table 7) [139]. Interoperability issues between datasets from different databases were shown by Suh et al. [140] and Ingwersen [141]. Furthermore, Ingwersen [141] identified interoperability issues as metadata/documentation consistency, LCI data exchange formats, product flow connectivity, background data connectivity, and elemental flow connectivity. According to Fritter et al. [139], the data exchange format and nomenclature present the greatest challenges to interoperability. A data exchange format is an agreement on how LCI data should be represented, and nomenclature refers to the actual naming of reference flows and entities within LCI datasets, as well as the categorization and organization scheme for LCI datasets [139,142]. The ILCD and EcoSpold (versions 1 and 2) data formats are currently the most widely used data exchange formats, with EcoSpold being the successor of SPOLD97 and SPOLD99 [139]. Both ILCD and EcoSpold are based on the Extensible Markup Language (XML) and are compliant with ISO/TS 14048, guidelines for format compliance [143]. In addition to ILCD and EcoSpold, another data exchange format is the JavaScript Object Notation for Linked Data (JSON-LD) format, which was introduced in

2015 as one of the formats used by openLCA. However, the use of this format in other software is still limited [143]. The common XML data encoding underlying ILCD and EcoSpold have enabled conversion between these data formats. For this purpose, the OpenLCA converter can be used. The converter is a tool to bridge the different data formats and nomenclature systems [144,145]. Since 2016, it has also been possible to convert SimaPro datasets using a separate mapping file [144–146]. Nonetheless, interoperability remains a persistent issue, as metadata can be lost between conversions due to differences in nomenclature, and errors occur when linking processes and flows [139]. In addition to individual LCI databases, dataset repositories or directories are available that can simplify the search for suitable datasets, facilitating data availability and interoperability. The Life Cycle Data Network (LCDN) was launched by the European Union in 2014. It is based on a node approach, where individual database providers manage their own locally hosted node. The individual nodes form a network, and the LCDN maintains a list of all published datasets and their respective nodes [147]. Another data platform for LCA data is the Federal LCA Commons, where LCA process data can be searched and downloaded for free. Data submissions are reviewed and approved by the National Agriculture Laboratory (NAL), and datasets are provided in both ILCD and JSON-LD formats. The geographic focus of the datasets is the United States of America [148]. OpenLCA Nexus is a web-based system that allows LCA data in ZOLCA file format to be searched, selected, downloaded, and purchased for use in the OpenLCA software. This means that the datasets can only be used by users of the OpenLCA software. While the ZOLCA file format cannot be converted using the openLCA Converter, it is possible to import ZOLCA datasets into the openLCA software and export them in another file format. However, interoperability may not be guaranteed in this case [114]. The Global LCA Data Access Network (GLAD) is the largest database directory currently available. It is managed by the Life Cycle Initiative of the United Nations Environment Programme (UNEP). In addition to searching datasets, GLAD also aims to enable an easy conversion between LCA data formats using new metadata descriptors and a global nomenclature mapping for elemental flows. A conversion tool is integrated into GLAD, allowing conversions between ecoSpold1, ecoSpold2, ILCD, and JSON-LD in any combination [149].

Table 7. Advantages and disadvantages of LCI databases.

Advantages	Disadvantages
• Databases can be used to fill data gaps when primary data are not available. • When generic datasets are used, the effort for data collection is reduced.	• Selecting appropriate datasets can be labor-intensive. • Generic data result in inaccuracies in the results. • Datasets are not always up to date. • Potential interoperability issues when using datasets from different sources. • Depending on the database, datasets need to be purchased.

3.4. Aggregation/Grouping

The aggregation/grouping approach aims to facilitate the collection, sorting and harmonization of LCI data by defining a data framework or grouping data according to a set of criteria, meaning that similar materials or components are summarized, thereby reducing the effort (Table 8). Favi et al. [150] created a structured model and data framework for the life cycle inventory of a generic welded structure. The data frame defines which data from the project documentation, such as welding instructions, CAD models, welding schedules, and material certificates, are relevant and provides the mathematical relationships for automatically generating the LCI based on the data. This way, the LCA can be conducted during the design phase. For the LCA in the sustainability report of Heidelberger Druckmaschinen, the material data from the bill of materials was divided into comparable material groups [36]. Specifically, the components from the bill of materials were clustered and calculated using aggregated mass balances. This was carried out to deal with very large amounts of data, given that numerous different materials are used in a printing press and it consists of around 70,000 different components that cannot be assessed individually. Keoleian et al. [33] assessed a generic vehicle using data from different models that were collected and summarized according to a vehicle code hierarchy. This was carried out due to time, data availability, and other project resource constraints that made it impossible to model each part in detail, e.g., each nut and bolt was not classified individually, but they were considered generally as fasteners.

Table 8. Advantages and disadvantages of the aggregation/grouping category.

Advantages	Disadvantages
• Reduction of time and effort for data collection. • Reduced complexity.	• The approach is useful for information structuring, but does not help in terms of performing the LCA calculations. • A workshop is necessary to define the individual cluster, resulting in additional effort. • Grouping of data reduces the accuracy.

3.5. Screening

Screening is a method for estimating the environmental impacts at the process, component, or input level to identify key parameters and decide where more detailed data are needed. This can reduce the complexity of the assessment as well as the data collection effort (Table 9) since only processes or flows that contribute significantly to the analyzed impact indicators are considered [14,16,21,23]. Typically, screening covers the entire life cycle and uses a variety of secondary data sources, such as LCAs of identical or similar products or generic datasets [16,21,23]. In principle, a purely qualitative analysis is also possible for screening purposes [14]. Fleischer et al. [14] presented an approach called iterative screening, which is aimed at reducing the effort associated with the collection of LCI data. In this method, five iteration steps that can be applied for screening purposes were proposed, whereby the effort for the LCA increases with each iteration step. For instance, in the first iteration step, only a qualitative assessment is performed, whereas in step five, a detailed quantitative assessment is carried out. In general, not all five iteration steps are carried out. Instead, the results are put in relation to the goal of the study after each step and a decision is made as to whether a more detailed assessment is necessary. Moberg et al. [151] used screening to perform a comparative life cycle assessment of e-books and paper books, with screening implying the use of generic data. Howe et al. [34] performed an LCA for a commercial aircraft. Since these consist of millions of parts and components, modeling all the parts is neither feasible nor possible, they focused only on the structural components. Non-structural components such as aircraft systems and internal components were neglected. The decision to focus only on the structural components, since they have the greatest weight and therefore are likely to contribute significantly to environmental impacts, can also be viewed as screening. Tufvesson et al. [152] analyzed various LCAs of so-called green chemicals to identify important parameters and methodological issues which are relevant to their ecological performance, to reduce the required effort for subsequent LCAs in this field. Saadatian et al. [153] identified and ranked the key environmental and cost factors of windows to reduce the LCA and cost evaluation effort in the early design phase. It is worth noting that there is disagreement in the literature about whether or not screening is considered a simplification category [21,23]. Like Gradin and Björklund [21], we decided to include screening as a category as limiting the focus of a life cycle assessment to key parameters can significantly reduce the data collection effort.

Table 9. Advantages and disadvantages of the screening category.

Advantages	Disadvantages
• Reduction of time and effort for the LCI phase, due to a more focused data collection process. • Reduction of complexity. • Useful for an initial assessment in the early design phase.	• Depending on the quality of the screening process, the neglection of components, life phases, etc., with significant contribution to the environmental impact can occur.

3.6. Others

The category "Others" includes approaches that cannot be assigned to one of the above categories or do not form a category of their own because the defined threshold of at least five studies to form a category was not reached. Valkama and Keskinen [154] tested different simplification modes by comparing simplified LCA variants, namely the use of average data as well as the reduction of the analyzed impact indicators, for three different electronic products with a more accurate LCA. Glatt et al. [155] developed a method for quantifying and reducing the environmental impacts of product-service systems, focusing exclusively on the cumulative energy demand (CED) category to reduce the effort and complexity of the assessment. Lewandowska et al. [156] attempted to find a methodological compromise between a holistic LCA and the mandatory energy performance certificate for buildings by comparing different simplification options, i.e., excluding life cycle phases or specific inputs and outputs, with a holistic LCA. Fleischer et al. [14] applied an approach called iterative screening and demonstrated this method using a case study from the automotive industry.

4. Discussion

As described in Section 1, several publications describe and categorize methods for simplifying LCAs [16,18–21,23]. The majority of relevant works was published in the twentieth century and consequently does not consider recent advances in the considered research field [16,18–20]. While other current reviews define their search strategies by connecting terms for describing simplification and terms for describing LCA, this article proposes another approach [21,23]. While simplifications are not always recognized or at least classified as such, this article tackles the task sort of from the other end. We did this by especially focussing on problems associated with the conduction of LCAs for complex products and by performing a two-stage literature search as described in Section 2. The obstacles identified during the preliminary search were used to derive search strategies for the comprehensive literature search using the PRISMA statement protocol. The systematic literature review is intended to provide transparency and ensure that no relevant information is omitted. Nevertheless, certain limitations cannot be excluded. The literature search was conducted in March 2022, and studies published later were solely added through snowballing. In addition, to ensure the thematic relatedness of the keywords a proximity operator of 10 words was used, and one of the identified obstacles (complexity reduction, time and effort reduction, structuring of LCI data) had to be included in the "TITLE-ABS-KEY" search field, resulting in potential omissions. This also applies to studies that deal with simplification methods but do not specifically mention one of the identified obstacles in the title, abstract, or keywords. Furthermore, several methods that were initially defined as simplification methods were neglected during this research as they correspond to the state-of-the-art approach for conducting LCAs as defined in international standards included in the ISO 14000 series (e.g., setting cut-off criteria, limiting system boundaries) [8,10,11]. The comprehensive literature search and the following clustering of publications resulted in several differences from other reviews in this field. Interestingly, some of the identified methods were also added as new simplification approaches in the reviews conducted by Beemsterboer et al. [23] and Gradin and Björklund [21]. In the review conducted by Beemsterboer et al. [23], parametric and modular approaches as well as automated data integration were stated as part of the simplification logic “automation” [23]. Gradin and Björklund [21] mentioned the modular approach as part of their “tool/database” category. Due to the fact that LCA software and related or stand-alone databases are a crucial element for conducting credible LCAs, this article provides a deep dive into the available offers of such. Although the list does not claim to be complete, it supplies LCA practitioners with a thorough overview and should help select the appropriate tool for each use case. In addition, the “automation” category primarily refers to interface methods that link LCA software with other software such as MS Excel or ERP systems. Approaches for estimating LCA results using artificial intelligence (AI) were not identified during the literature search. Consequently, the application of AI was not discussed in detail although the technology is attributed with great potential at least for reducing corporate GHG emissions [157]. Similarly, automatic data collection using sensors in production and ultimately generating a digital twin of the production infrastructure and the subsequent use of the acquired data as LCI was not discussed, although several publications discussed the potential benefit for the conduction of LCAs [158–160]. Consequently, further research should focus on the potential of digitization for assisting LCA practitioners by automated LCI data acquisition and its standardized incorporation into LCA software or connection with impact data.

5. Conclusions

Various simplification methods for conducting life cycle assessments of products are presented in literature. This review focused on approaches that addressed the objectives of reducing effort during the conduction as well as the complexity of the process. Furthermore, the structuring of data is desirable as especially the LCI of complex products often is extensive and confusing. For all the identified clusters of simplification approaches, several executions are documented in the literature. The feasibility under defined circumstances is thus demonstrated and the benefits associated with the execution are described. Nevertheless, relevant barriers remain and all five simplification approaches are associated with disadvantages that often concern the accuracy of the obtained results as components or life phases are neglected (screening), or detailed evaluations are not possible on a input-/output level (parametric). Furthermore, the initial utilization of simplification methods is often accompanied with the relevant efforts for determining mathematical correlations (parameterization), or defining data interfaces and standards for data quality (automation). Furthermore, all simplifications of the standardized LCA process need to be comprehensibly justified and documented in order to ensure transparency, which is one of the main principles for conducting credible PCFs, as described in ISO 14067, again, resulting in additional effort. Consequently, certain simplification approaches are only applicable for LCA practitioners that aim to conduct several LCAs, building up competencies and reuse findings from each assessment. Additionally, some approaches are based on expert opinions and thus the results are influenced subjectively (aggregation/grouping, screening).

The applicability of simplification approaches is highly dependent on the considered product and further circumstances (especially concerning the further usage of results when, for example, comparison with other products). LCA practitioners thus face the challenge of examining which simplification method results in the relevant benefits during the conduction of LCAs, while not reducing the quality of the results to an unacceptable extent.

Finally, it can be stated that simplification methods exist for the first three phases of an LCA (as defined in ISO 14040), but not for the final phase of interpretation.

6. Future Prospects

Future work should focus on the effects of simplification methods on the overall results as well as on the combination of different methods. For the transfer to real-world applications, it is necessary to further investigate the integration of simplification approaches into corporate practices and data management. As no binding norms exist for the applicability of simplification methods, further research should address the definition of circumstances under which certain simplifications of the process of LCA are acceptable. While doing so, the compatibility of such procedures with current LCA standards needs to be investigated.

Concerning the review at hand, further detailing should address the automated data acquisition in the production infrastructure by the integration of sensors and enablers for digital twins, for example, the asset administration shell. Furthermore, AI technologies, such as machine learning and artificial neural networks might bear the potential to significantly reduce the effort for data handling and interpretation. The literature that analyzes the role of such approaches in the process of LCA should be analyzed explicitly.

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