Resources, Conservation & Recycling 200 (2024) 107291

Contents lists available at ScienceDirect

Resources, Conservation & Recycling

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

From LCA to circular design: A comparative study of digital tools for the built environment

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A R T I C L E I N F O

Keywords:
Circular construction
Sustainability
Bibliometric analysis
Life cycle assessment (LCA)
Building information modeling (BIM)
Computational design (CD)

A B S T R A C T

This paper reviews digital tools for supporting the Circular Economy (CE) in the built environment. The study provides a bibliometric analysis and focuses on computer-aided design (CAD), building information modeling (BIM), and computational plugins that can be used by practitioners. While Life Cycle Assessment (LCA) is the primary methodology for evaluating buildings' environmental performance, the study identifies tools beyond LCA, including computational methods and circularity indicators, that can support the evaluation of circular design strategies. Our review highlights limitations in tools' functionalities, including a lack of representative data for LCA and underdeveloped circularity indicators. The paper calls for further development of these tools in terms of interoperability aspects, integration of more sources of data for LCA and circularity, and possibilities for a comprehensive evaluation of design choices. Computational plugins offer greater flexibility, while BIM-LCA integrations have the potential to replace dedicated LCA software and spreadsheets. Additionally, the study identifies opportunities for novel digital methods, such as algorithms for circular design with various types of reused building elements, and sharing of digital twins and material passports. This research can inform future studies and support architects and engineers in their efforts to create a sustainable built environment.

1. Introduction

The built environment is a major contributor to global resource depletion and environmental impacts, accounting for 50 % of all extracted raw materials and approximately 40 % of energy-related CO_2 emissions (World Green Building Council, 2021). To address these challenges, the Circular Economy (CE) has gained increasing attention as a means to promote sustainable development and decouple economic growth from resource consumption (Benachio et al., 2020; Geissdoerfer et al., 2017). The European Union (EU) has made the CE a key objective of its Green Deal (European Commission, n.d.-a), where the EU Taxonomy for sustainable activities sets technical requirements for six environmental objectives, including a CE, climate change mitigation, climate change adaptation, water, pollution, and biodiversity (European Commission, n.d.-c). In relation to this, the Energy Performance of Buildings Directive (EPBD) aims to increase the rate of renovation and circularity of buildings, and to require the reporting of whole life cycle emissions for new buildings (European Commission, n.d.-b).

Lovrenčić Butković et al. (2023) identified five major topic categories for achieving a CE in construction: waste management (i.e., reuse and recycling), reducing the impact on the environment, material and product design, building design, and policies. Their study found that Life Cycle Assessment (LCA) was the most widely used assessment method to support decisions for a CE in construction projects. Other methods used in CE studies, sometimes in combination with LCA, included Life Cycle Costing (LCC), Cost-Benefit Analysis (CBA), and Material Flow Analysis (MFA). Various design and construction strategies have been identified to reduce the environmental impacts of buildings, such as extending the lifespan of buildings, implementing flexible and adaptable designs, and reusing and recycling building materials (Malmqvist et al., 2018). For instance, concrete production is responsible for 8–9 % of the global anthropogenic CO_2 emissions (Monteiro et al., 2017), and around 30 % of the total mass of solid waste in Europe (Böhmer et al., 2008). Küpfer et al. (2023) found that the reuse of extracted concrete for new structures has been shown with successful applications, as well as resulted in cost savings and reduced environmental impacts. The findings of these studies are consistent with policies and regulations aimed at reducing the carbon footprint of construction, by establishing benchmarks and emission limits, and circularity criteria, providing evidence in support of these objectives (Birgisdóttir, 2021; Boverket, 2020; European

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https://doi.org/10.1016/j.resconrec.2023.107291
Received 6 April 2023; Received in revised form 15 October 2023; Accepted 25 October 2023
Available online 15 November 2023

Commission, n.d.-d; Parliamentary Office of Science and Techonology UK, 2021; World Green Building Council, 2022).

1.1. Towards digital methods for environmental performance

Digital technologies have been argued to support the United Nations' Sustainable Development Goals (SDGs), including those related to construction (Bai et al., 2020; United Nations, 2015), and to play a critical role in enabling a CE for the built environment (Çetin et al., 2021). Until recent years, LCA has been perceived as far from the domain of architects, being considered complicated and time-consuming. However, integrating LCA into the architectural design process was found to positively influence design choices (Naboni, 2017). A study on carbon assessments in Australia identified the following challenges in practice: the need for expert knowledge, lack of accurate data and benchmarks, inconsistent methodologies, and the lack of integrated LCA tools for building designers (Fouché & Crawford, 2015). However, recent studies on building information modelling (BIM) for LCA have shown promising results, with reductions in time and effort required at each design stage (Hollberg, Genova, et al., 2020). To increase the accessibility and feasibility of LCA for practitioners, new tools and databases are continuously being developed and proposed (Amahmoud et al., 2022; Dalla Mora et al., 2020; Gomes et al., 2019; Hollberg, Kaushal, et al., 2020; Soust-Verdaguer et al., 2017; Tam et al., 2022; Theißen et al., 2020; Wastiels & Decuypere, 2019). The development of digital tools and databases presents a significant opportunity to improve LCAs and establish industry benchmarks. However, to enable comparable LCAs, there is a need for transparent and consistent methodologies (De Wolf et al., 2017). De Wolf et al. (2020) compared LCA methods for recycled/reused products and found that current practice prevents reliable comparisons, and proposed breaking down the LCA into three assessments, refining evaluations with uncertainty analyses, and the need to develop quantitative and qualitative criteria for the environmental impact assessment of reused components in buildings. Addressing these challenges will be crucial to achieving a CE in the built environment.

This paper aims to assess the current state of digital tools used in the context of a CE in the built environment. To achieve this aim, the paper has the following objectives:

1. Explore assessment methods, digital technologies, and emerging trends related to the CE.
2. Conduct a comprehensive literature review and bibliometric analysis focusing on the intersection of CE and digital methods/tools for architectural/building design.
3. Analyse and compare the existing digital tools to determine their effectiveness, gaps, limitations, and areas for further development in support of CE objectives.

To set the focus for this review, an exploratory search in the scientific and professional literature was done first (Section 2). The approach of this study is dual: one part provides a bibliometric analysis of the literature, and the other part analyses available tools and workflows for practitioners and compares the tools across criteria in support of a CE. The study started in March 2022 and the last search was performed in June 2023. The details are given in the Methods (Section 3) and Fig. 1.

1.2. Contribution and prior related studies

Previous research has investigated various aspects of integrating digital tools and environmental assessment methods like LCA for building designers. These include the integration of BIM and LCA (Dalla

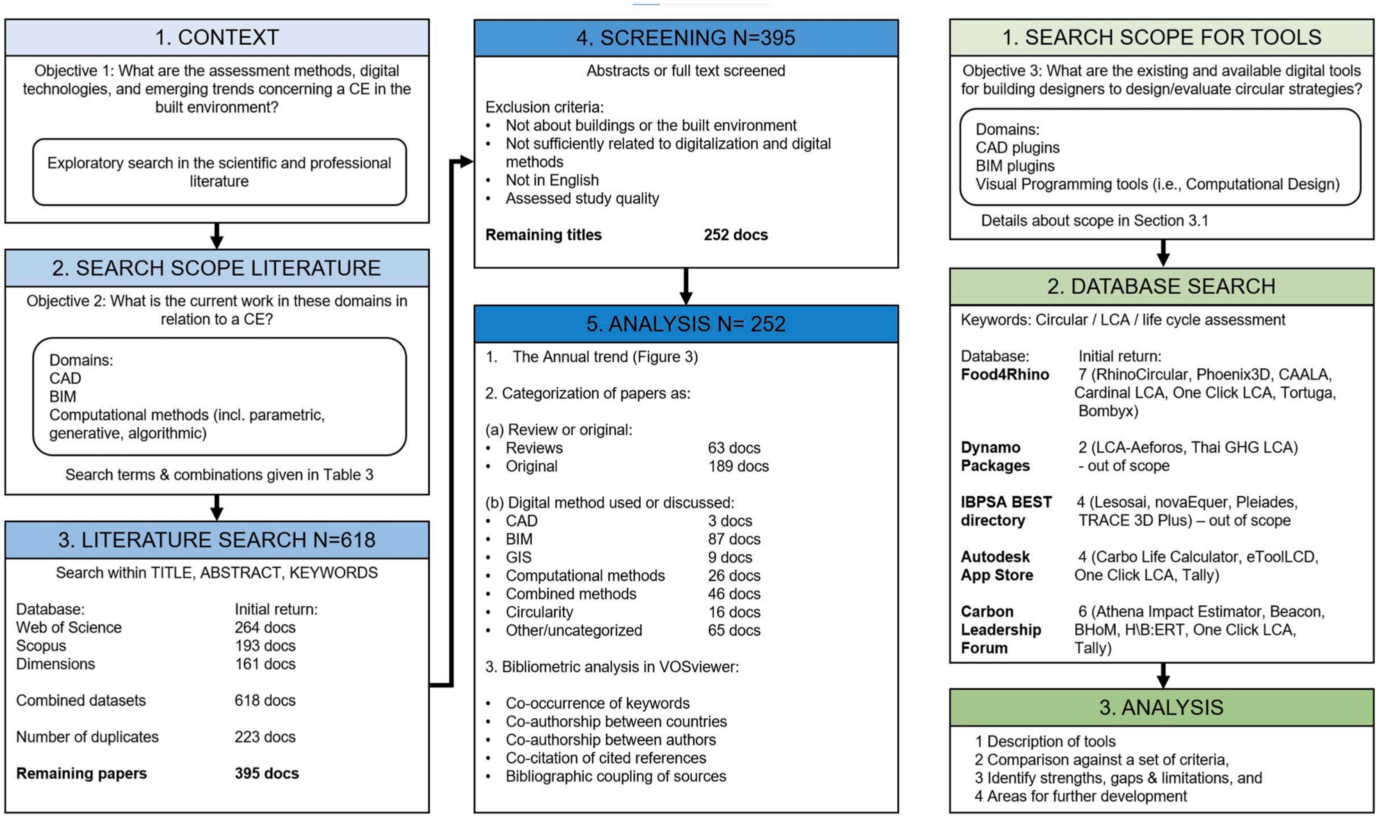

Fig. 1. Roadmap for bibliometric analysis (left) and review of available digital tools (right). The papers selected for analysis (step 5) are categorized based on the digital methods employed or discussed. The category 'Computational methods' encompasses papers on computational design and artificial intelligence. The 'Circularity' category includes papers on C-indicators, experiments, and simulations. Papers describing two or more digital methods are categorized as 'Combined methods'. Papers that do not explicitly reference a digital method are labelled as 'Other/uncategorized'.

Table 1
Previous studies on LCA and/or CE.

Study	Summary	LCA	CE
Dalla Mora et al. (2020)	Reviews research on BIM-LCA integration.	✓	
Potrč Obrecht et al. (2020)	Reviews BIM-LCA workflows and case studies.	✓	
Wastiels & Decuypere (2019)	Categorizes BIM-LCA integration strategies.	✓	
Apellániz et al. (2021)	Presents a parametric design tool for LCA – One Click LCA.	✓	
Basic et al. (2019)	Presents a parametric design tool for LCA – Bombyx.	✓	
Płoszaj-Mazurek et al. (2020)	Estimates the carbon footprint through parametric design and machine learning methods.	✓	
De Wolf et al. (2023)	Discusses LCA tools and databases, and provides criteria for their characterization to support the Level(s) framework.	✓	
Di Bari et al. (2022)	Survey for Building LCA tools and procedure to identify tools based on user needs.	✓	
Hollberg et al. (2022)	Develops and tests a user-centric framework and early design tool for LCA.	✓	
Säwén et al. (2022)	Develops a characterisation framework for parametric building LCA tools.	✓	
Al-Obaidy et al. (2022)	Presents a parametric approach to optimize sustainable construction design, with a focus on environmental impacts and circularity (reuse content).	✓	✓
Brütting et al. (2019)	Presents a structural optimization method for the design of truss structures incorporating reuse.	✓	✓
Huang et al. (2021)	Introduces an algorithmic workflow for the reuse of structural elements.		✓
Honic et al. (2023)	Proposes a bottom-up approach using BIM and GIS to assess material quantities.		✓
Turan & Fernández (2015)	Presents a method to estimate the material stock and flows of building materials in an urban area.	✓	✓
Weber et al. (2022)	Reviews automated floorplan generation methods, useful for assessing material quantities in the building stock.		✓

Mora et al., 2019; Potrč Obrecht et al., 2020; Soust-Verdaguer et al., 2017; Wastiels & Decuypere, 2019), the use of parametric design methods for LCA (Apellániz et al., 2021; Basic et al., 2019; Hollberg, Kaushal, et al., 2020), and the characterization of LCA tools for practitioners (De Wolf et al., 2023; Di Bari et al., 2022; Hollberg et al., 2022; Säwén et al., 2022). Additionally, some studies have explored the use of computational methods (Al-Obaidy et al., 2022; Brütting et al., 2019; Heisel & Nelson, 2020; Huang et al., 2021; Płoszaj-Mazurek et al., 2020; Warmuth et al., 2021), while other studies proposed digital methodologies for estimating material quantities of the building stock for a CE (Honic et al., 2023; Turan & Fernández, 2015; Weber et al., 2022, p. 3). Table 1 provides further details on prior studies. Emerging methodologies have also been proposed for CE indicators which are described in Section 2.2. However, limited attention has been given to exploring the potential of digital tools beyond LCA for achieving a CE in buildings. This paper aims to fill this gap by identifying and assessing the possibilities offered by digital tools, including CAD and BIM tools and computational methods, to support practitioners in evaluating circular design strategies. This is particularly relevant in the context of new building regulations that aim to reduce the carbon footprint of projects through LCA and promote a CE in the construction sector. The next section provides a brief literature review on LCA, circularity indicators, and developments in regulations, followed by the methods section that describes the bibliometric analysis and the process of identification and comparison framework for tools. The results and discussion section summarizes the limitations and opportunities of these tools and identifies areas for further research. The findings of this study can inform the development of digital tools that better align with regulatory requirements and support the evaluation of circular design strategies for practitioners.

2. Literature review

2.1. Life cycle assessment

LCA evaluates the environmental impacts of a product or system throughout its entire life cycle (International Organization for Standardization 2006a, 2006b). In Europe, the assessment of buildings' environmental performance is carried out using LCA, as described in the EN 15978 standard (European Committee for Standardization, 2011). While there are several environmental impact indicators considered in a complete LCA, a greater focus has been on policies aimed at reducing greenhouse gas emissions (GHG) to address climate change as a priority for the construction industry. The Global Warming Potential (GWP) indicator measures the total GHG of a product or process. The following terms are related to the environmental impacts of buildings but may refer to different stages of a building's life cycle.

- Embodied Carbon (EC) represents emissions arising from the manufacturing, transportation, installation, maintenance, and disposal of building materials at the end of life (Carbon Leadership Forum, 2020; London Energy Transformation Initiative, 2020), 2020). Embodied carbon accounts for 11 % of global emissions (World Green Building Council, 2019).
- Upfront Carbon (UC), a term commonly used in professional guidelines, refers to emissions associated with the manufacturing, transportation, and construction (i.e., A1 – A5 LCA modules) (World Green Building Council, 2019).
- Operational Carbon (OC) relates to emissions from energy use during building operation, representing around 28 % of global energy-related CO2 emissions (World Green Building Council, 2019).
- Whole Life Carbon (WLC) refers to the total carbon emissions, including both EC and OC emissions (Carbon Leadership Forum, 2020; London Energy Transformation Initiative, 2020).
- Whole Building LCA (WBLCA), or simply 'building LCA', is a comprehensive evaluation of the environmental impacts of a building over its entire life cycle. It includes embodied carbon and operational emissions and a range of impact categories (American Institute of Architects (AIA) & Carbon Leadership Forum, n.d.; Simonen et al., 2019).

A review of 650 LCA studies found that better energy performance reduced life cycle carbon emissions, and in turn led to a relatively larger contribution coming from embodied GHG emissions (Röck et al., 2020). This emphasizes the urgency for reducing embodied emissions, which may cause half of the carbon footprint of new buildings by 2050 (World Green Building Council, 2019).

2.2. Emerging circularity indicators

Achieving a CE for buildings requires various initiatives such as policies that promote deconstruction and reuse rather than demolition, the use of assessment methods like LCA, and ensuring reliable digital information such as material passports for reusing building materials (van Eijk et al., 2021). A material passport (MP) is a digital document containing information about materials, a product or a system used in the construction of a building (Hoosain et al., 2021). MPs can gather information from several sources, can be accessed by stakeholders, and can facilitate the implementation of sustainability and CE measures in the construction industry. There is not a widely accepted definition of

MP and other terms exist such as Digital Product Passports (DPP), while more information can be found in the literature (Çetin et al., 2023; Jansen et al., 2022).

Various indicators have been proposed by organizations and academia to measure the circularity of services and products, and some of these have been adapted for buildings. The Material Circularity Indicator (MCI) is one of the most well-known circularity indicators (C-indicators) (Ellen MacArthur Foundation & Granta Design, 2015). MCI focuses on the amount of used virgin materials, the amount of unrecoverable waste and the lifetime of the products (Cottafava & Ritzen, 2021, p. 1). MCI has been adapted for application to buildings by Madaster (2018), a digital platform for a CE. Cottafava & Ritzen (2021) proposed a Building Circularity Indicator (BCI) that combines the MCI with embodied energy, embodied emissions, and design for disassembly criteria. Göswein et al. (2022) proposed a Circular MP that provides information on construction products for evaluating their circularity potential for reuse and recovery. Hence, some information in MPs could be used to calculate C-indicators. Other indicators based on the MCI are the Circular Economic Value (CEV) and the Circular Economy Indicator Prototype (CEIP) (Corona et al., 2019), but these have not been adapted yet for evaluating the circularity of buildings.

Corona et al. (2019) argued that current C-indicators indicate aspects such as material reuse, resource efficiency, material value retention, or economic value, but fail to capture other critical aspects, which could lead to an incomplete understanding of CE. In their study, the MCI and Cumulative Service Index (Circ(T)) are criticized for providing a narrow view of CE by focusing solely on material recirculation, and not well suited to assess whether there is an actual reduction in resource consumption, which in turn could lead to higher energy consumption and pollution. Saidani et al. (2022) further explained that some inputs of LCA are also used in the MCI, but such evaluation is not yet standardized.

Corona et al. (2019) suggested that future development of C-indicators should build on assessment methods like LCA or MFA, while in another review Khadim et al. (2022) recommend developments for digital technologies like BIM and open access databases to facilitate evaluations. In addition, some studies argued that 'CE and 'Sustainable Development' are not synonymous, and trade-offs may occur between the two (Blum et al., 2020; Corona et al., 2019; Saidani & Kim, 2022). Blum et al. (2020) suggested that the evaluation of circularity should be complemented with economic, social, and environmental aspects. Table 2 provides a summary of prior studies.

2.3. Regulations and voluntary standards

Prior research has categorized indicators of certification systems as (a) performance indicators aimed to assess a sustainability aspect and (b) feature indicators that assess whether a strategy is in place (Wangel et al., 2016). Green building certifications like BREEAM and LEED (Building Research Establishment (BRE), 2021; U.S. Green Building Council, 2021) have both performance and feature indicators. For example, LEED v4.1′s credit for building life-cycle impact reduction requires a reduction in GWP and two other impact categories while ensuring that other impacts do not increase by more than 5% compared to a baseline building. The baseline design can be set by the project team. The LEED credit also incentivizes the reuse of building materials to receive additional points for the certification.

On the other hand, regulations mandating sustainability measures are becoming more prevalent in Europe. France, the Netherlands, and Nordic countries now require projects to disclose their carbon emissions (Boverket, 2020; Ministry of the Ecological Transition (France), 2020). France, Denmark, and the Netherlands already enforce life cycle emissions limits for new buildings. The Dutch environmental assessment method utilizes weighted factors across ten impact categories to determine a single indicator of environmental performance (National Environmental Database, n.d.). These regulations reflect a growing trend towards greater accountability of construction projects in Europe where the role of digital tools is crucial to support designers from an early stage to evaluate design alternatives, including circularity strategies, and work towards compliance with limit values. Additionally, there are differences in LCAs due to methodological choices, or the assessment methods required by regulations, such as the LCA modules, scope of building elements, and calculation period, which make it challenging to compare results across projects and contexts (Moncaster et al., 2019; One Click LCA, 2022; Ramboll Buildings, 2022; Rasmussen et al., 2018). Furthermore, the need for harmonized methodologies has been argued in earlier research (De Wolf et al., 2017; Rodriguez et al., 2019), and is now an objective of the 'Transition Pathway for Construction' in Europe (European Commission, 2023), and there is work towards harmonization in Nordic countries (*Nordic Sustainable Construction*, n.d.).

Table 2
Summary of previous studies on C-indicators.

Study	Summary
Cottafava & Ritzen (2021)	Explores the use of C-indicators, the BCI and novel BCI (NBCI), and Design for Disassembly criteria in environmental assessments of the built environment.
Heisel & Rau-Oberhuber (2020)	Based on a case study, it describes the potential of materials passports and the Madaster Circularity Indicator in documenting material stocks and flows and supporting the transition towards a CE in the construction industry.
Corona et al. (2019)	Reviews emerging C-indicators for a CE concerning the sustainable development concept, highlighting their limitations and the need to address all dimensions of sustainability.
Saidani & Kim (2022)	Explores the relationship between circularity and sustainability indicators, and highlights shortcomings between different approaches and indicators.
Khadim et al. (2022)	Reviews 35 existing building circularity indicators, highlighting their limitations, and argue for the need to develop a common framework.

Table 3
Keywords used for the literature search in web of science, scopus, and dimensions.

	Groups of keywords that are connected by AND		
Keyword/Group	1	2	3
Keywords within a group that are connected by OR	Circular economy	Computer aided design	Building
		Computer-aided design	Building design
		CAD	Architectural design
		Building information modelling	Built environment
		BIM	Construction
		Parametric	Construction industry
		Parametric design	
		Computational	
		Computational design	
		Algorithm	
		generative	

3. Methods

This section describes the bibliometric analysis, the scope of digital tools considered, and the criteria utilized in the comparison framework. The literature search was conducted in the three prominent scholarly databases: Web of Science, Scopus, and Dimensions (Visser et al., 2021). Table 3 provides the three groups of keywords used in the search. The literature review process and search for digital tools follow the steps presented in Fig. 1. To create and visualise bibliometric network maps, such as on the most used keywords and countries with the largest publications, the software VOSviewer was used (van Eck & Waltman, 2014). A bibliometric network consists of only one item (e.g., keywords, journals, countries) and links, where the latter represents the connection between items such as co-authorship.

3.1. Scope and delimitations

This study also aims to identify existing digital tools that can be used by practitioners. In this regard, we considered digital tools (i.e., plugins) for CAD and BIM design environments. We also considered computational design approaches, which are increasingly favoured by practitioners for their ability to create customized workflows aligned with design objectives, provide iterative feedback in the design process, and combine different workflows (Dogan & Jakubiec, 2022). To clarify, ‘computational design’ is used as an umbrella term for parametric, algorithmic, and generative design (Caetano et al., 2020). Dynamo and Grasshopper are among the most widely used visual programming languages in computational design (Säwén et al., 2022, p. 2). Rhinoceros 3D and Revit were also commonly used in the literature and among practitioners (Potrč Obrecht et al., 2020, p. 8; Reinhart et al., 2013, p. 478), likely due to their extensive developer documentation and open Application Programming Interface (API), which facilitates the development of plugins and visual programming components.

The scope of this study includes tools that:

- are plugins for CAD, BIM, and computational tools.
- perform an LCA or embodied carbon calculation.
- are for circular design or C-indicators.
- can be used by architects and engineers in their design workflows at any stage.
- are available in the English language.
- are not standalone LCA software for environmental experts.

Although tools other than Revit and Rhinoceros 3D, as well as tools used in non-English-speaking contexts, may also be relevant to the analysis, it makes sense to limit the scope of the study. Any additional tools identified during the writing of this paper that are worth mentioning but outside the strict scope, have been referenced to provide a broader perspective. For instance, there is a recent LCA plugin for Archicad developed for the Danish context, and new web-based tools were also reported in this study.

Table 4
Representative sample of existing digital tools for environmental impacts and circular design.

Tool	Web-based tool	Visual programming tool	CAD plugin	BIM plugin	Citation
Beacon by Thornton Tomassetti				✓	(Thornton Tomasetti CORE Studio, 2020)
Bombyx		✓	(✓)		(Basic et al., 2019; ETH 2022)
Buildings and Habitats object Model (BHoM)		✓	(✓)	(✓)	(The BHoM, 2022)
CAALA	✓	(✓)	(✓)	(✓)	(Hollberg et al., 2018)
Carbo Life Calculator				✓	(Veld, 2023)
Circular EcoBIM		✓		✓	(Circular EcoBIM, 2022)
DesignLCA for Archicad				✓	(Graphisoft Center Denmark, 2022)
EPIC by EHDD Architecture	✓				(EHDD Architecture, n.d.)
EPIC for Grasshopper		✓	(✓)		(Crawford et al., 2022b)
eToolLCD	✓			(✓)	Cerclos (Autodesk, n.d.-a)
Hawkins\Brown Emission Reduction tool (HBERT)				✓	(Hawkins\Brown, 2022)
LCA-Aeforos		✓		(✓)	(Autodesk, n.d.-b)
One Click LCA	✓	✓	✓	✓	(Apellániz et al., 2021; One Click LCA, n.d.-a, n.d.-b, n.d.-c)
Phoenix 3D		✓	(✓)		(Structural Exploration Lab, n.d.; Warmuth et al., 2021)
Rhino Circular		✓	(✓)		(Heisel & Nelson, 2020)
tallyLCA				✓	(Building Transparency, 2021)
Tally Climate Action Tool (tallyCAT)	(✓)			✓	(Building Transparency et al., 2022)
Tortuga for Grasshopper		✓	(✓)		(Tortuga - LCA in Grasshopper, n.d.)

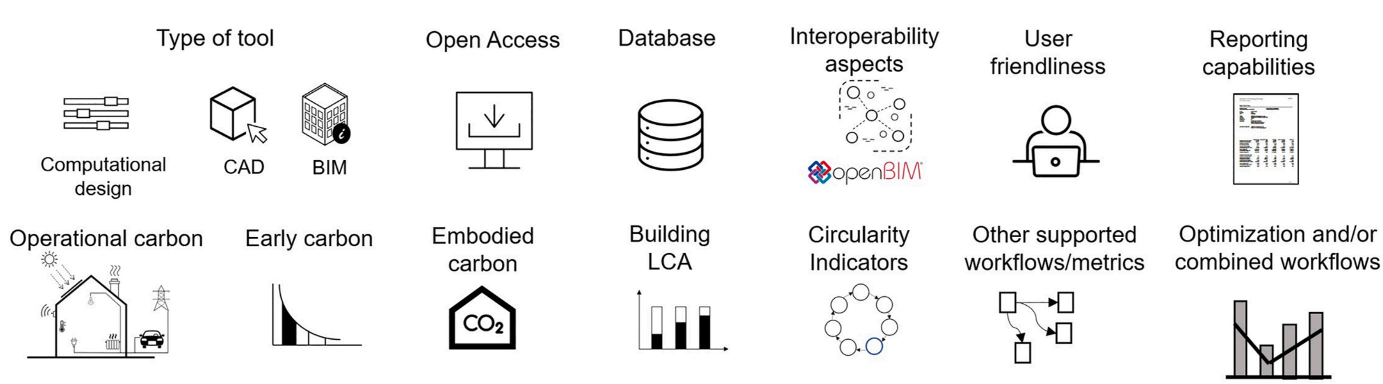

Fig. 2. Comparison framework for digital tools.

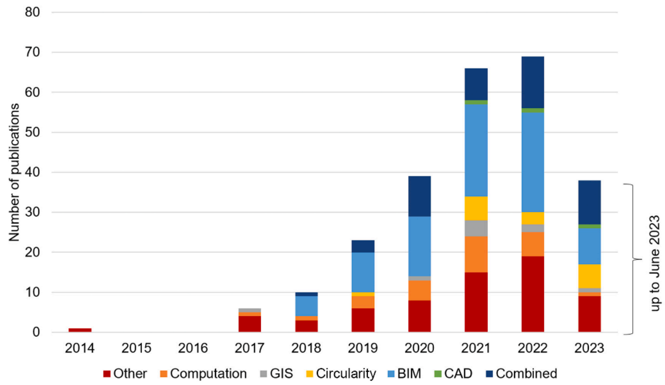

Fig. 3. Annual trend in the number of scientific peer-reviewed publications on CE within the defined search scope and screening. Papers for the year 2023 are up to June 2023 when the last search was performed.

3.2. *Survey of digital tools*

To identify digital tools, a survey was conducted across various databases and sources. These included the 'BEST directory' (IBPSA-USA, n.d.), 'Dynamo Packages' (Autodesk, n.d.-a), the Autodesk App Store (Autodesk, n.d.-b), and 'Food4Rhino' (Robert McNeel & Associates, n.d), as well as resources provided by the Carbon Leadership Forum (AIA & Carbon Leadership Forum, n.d.). Table 4 provides a snapshot of digital tools at the time of writing. When a tool is developed on one platform and interacts with other interfaces, this is indicated in brackets for the secondary interface.

The following sections omit tools that rely solely on the exchange of a 'bill of quantities', such as the 'Impact Estimator for Buildings', or based on model exchange such as eToolLCD or via gbXML, including 'CAALA' (Athena Institute, n.d.; Caala GmbH, n.d.). Although these tools were deemed usable by architects, as indicated on their websites, they do not allow importing results back into the CAD or BIM environment for feedback and visualization. Plugins like 'LCA-Aeforos' and 'Tortuga for Grasshopper' that have not been developed for more recent versions of Revit and Rhino are also excluded, where the latest version for each is dated in 2015 and 2016 respectively.

3.3. *Comparison framework*

The comparison of tools was based on a set of criteria, including tool type, database, performance indicators, interoperability aspects (e.g., data/file exchange approach), and criteria for utilizing digital technologies such as user-friendliness, reporting capabilities, other supported workflows of the plugin, and flexibility to combine with other tools and workflows. The complete list of criteria is illustrated in Fig. 2 and discussed in detail in the subsequent paragraphs. The user-friendliness score was assessed on a scale from 1 to 5, based on literature related to each tool.

3.3.1. *Environmental performance*

The literature review was used to identify categories of indicators for environmental impacts and circularity for buildings. LCA is considered

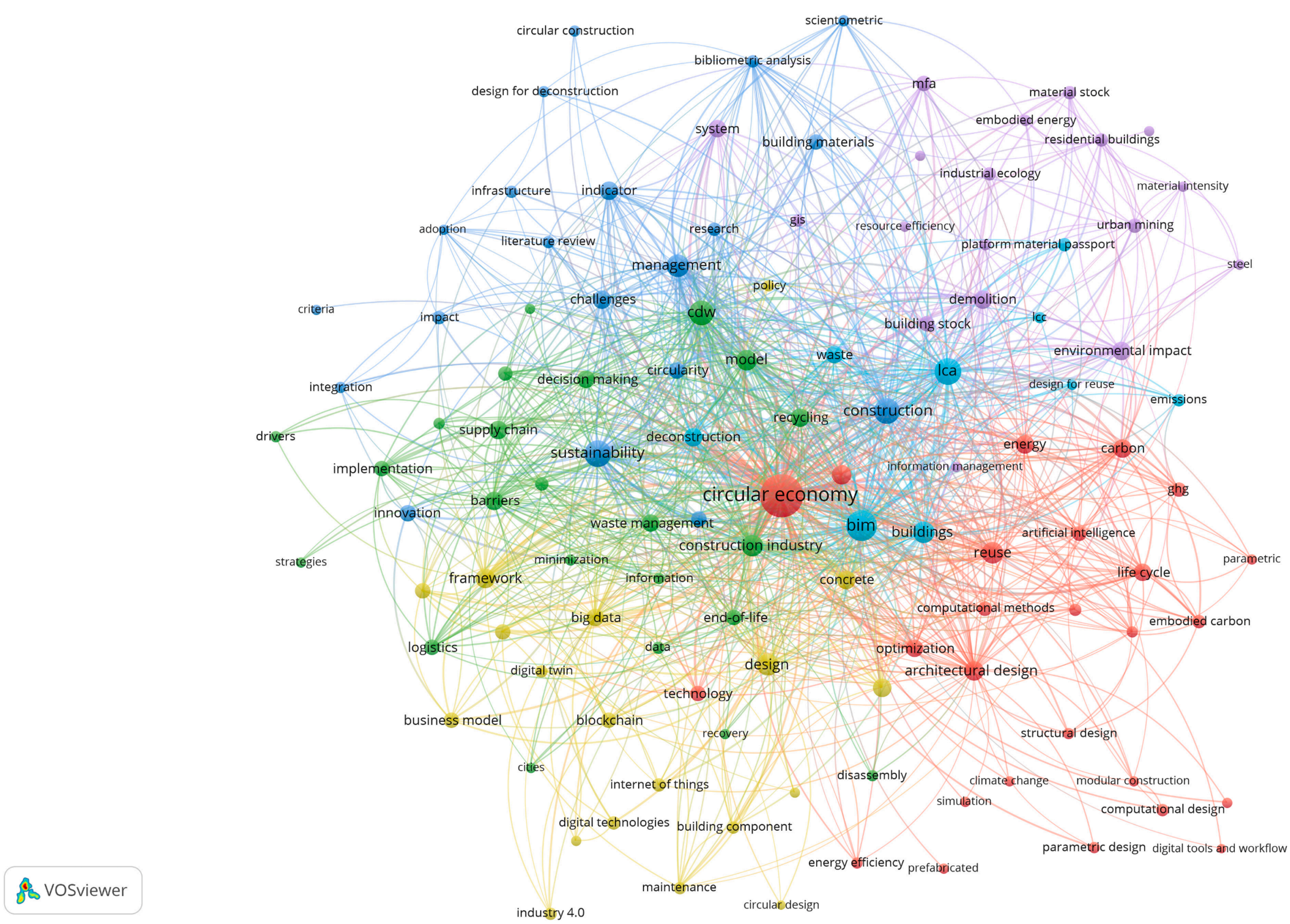

Fig. 4. Most frequently used keywords in CE research within the search domain. The co-occurrence network map visualises the interconnectedness of these keywords based on the number of documents in which they appear together. The circle size indicates the number of occurrences of the term. The colours indicate identified clusters of terms by the VOSviewers' algorithm.

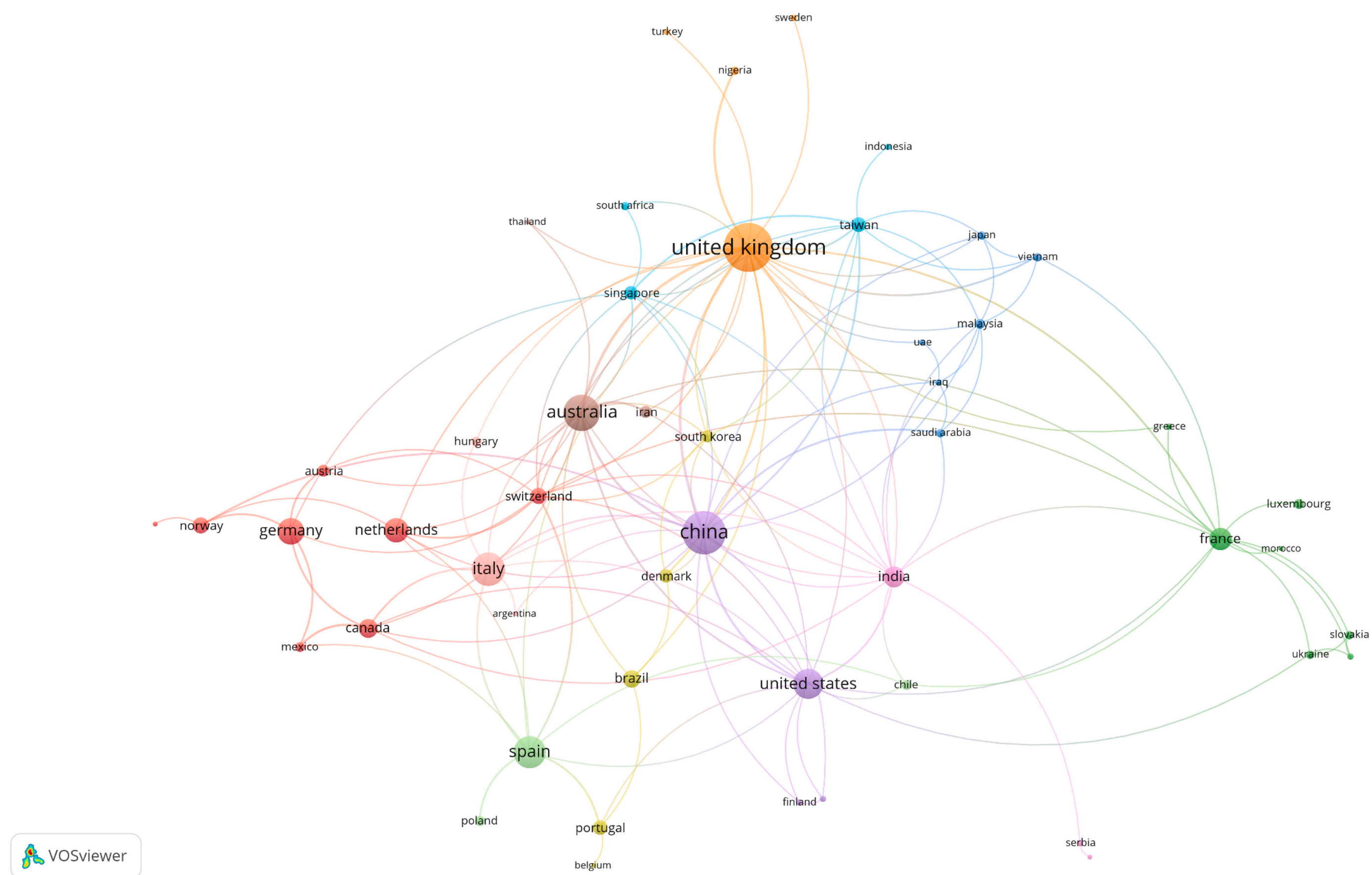

Fig. 5. Co-authorship between countries. The size of the circles indicates the number of documents per country.

one of the most used assessment methods for a CE and is organized into three criteria that are: embodied carbon, operational carbon, and building LCA. C-indicators are presented in one category. Additionally, 'early carbon optimization' is introduced as a separate criterion from embodied carbon. Reducing the carbon footprint at earlier design stages was emphasized frequently in the literature. The term 'early carbon' is used in this study to refer to digital tools and workflows that (1) provide estimates of environmental impacts based on building types and parameters, (2) allow for comparisons between building components and assemblies of CAD/BIM models, or (3) use computational methods to enable new digital workflows.

3.3.2. *Interoperability aspects*

Interoperability is the ability to exchange and use information between different systems and organizations (BIM Dictionary, n.d.; Turk, 2020). It encompasses systems, processes, and file formats, but not necessarily open file formats. The ISO 19650 standard recommends the use of open standards whenever possible when working with BIM (International Organization for Standardization, 2018b, 2018c), and buildingSMART promotes the use of open standards through the 'openBIM' initiative (buildingSMART International, n.d.). The Industry Foundation Classes (IFC) is a data schema and an exchange file format structure, outlining how building information should be organized and represented, under ISO 16739-1:2018 (International Organization for Standardization, 2018a). The IFC has been adopted in multiple file formats e.g., STEP Physical File, XML. These formats facilitate information exchange in the construction industry. While data exchange through APIs and plugins is more common, Turk (2016) emphasizes the role of standards in BIM as "*(1) they provide the lowest common denominator for information exchange, (2) a reliable long-term information storage, and (3) a neutral environment for academia to contribute to BIM research*". As an example, the use of non-proprietary open file formats is required for large public projects in Italy (Ministry of Infrastructure and Transport Italy, 2021). Support for open standards like the IFC is therefore critical, also in consideration of emerging climate regulations. Efforts using BIM and the IFC for building permits are underway in Estonia, the Czech Republic and Singapore (Noardo et al., 2022), and compliance with GHG limit values could be verified using BIM models along in the permitting process. Digitalization of these processes was recently approved in legislation in Finland and is expected in 2025 (Ministry of the Environment Finland, 2023). Another initiative worth mentioning is the buildingSMART Data Dictionary (bSDD) (Tomczak et al., 2022). It is an online service and reference library for enriching models (i.e., extending the IFC), which includes classification systems, definitions, properties and their allowed values, units, and translations. Hence, the bSDD provides a common framework for accessing and connecting different definitions for the construction industry, improving data quality and consistency. The criterion used in Table 8 is to "enrich and align data schema e.g., with the IFC, bSDD definitions.

3.3.3. *Criteria for utilizing digital technologies*

To comprehensively evaluate circular design strategies, it may be necessary to use additional indicators beyond those identified in this study on sustainability aspects, where further details can be explored in the literature (Dervishaj, 2023; Dervishaj et al., 2022). This is particularly important when considering emerging regulations and the need to analyse trade-offs, as highlighted in previous studies on CE indicators. As such, the flexibility of tools to assess multiple indicators, combine with workflows of other tools, and/or link to optimization tools is considered a relevant criterion. Any additional features or metrics provided by the reviewed tools will be reported in the results section.

The user-friendliness of digital technologies is an important factor in

Table 5
Ranking of keywords from analysis in VOSviewer. A VOSviewer thesaurus file was prepared to merge different variants of similar keywords in the network map. Keywords with at least 10 occurrences are reported. The 'link strength' is the number of documents in which two keywords appear together. The 'total link strength' refers to the sum of the link strengths of an item in a network visualisation.

Rank	Keyword	Occurrences	Total link strength
1	Circular economy	126	784
2	BIM	52	378
3	LCA	38	299
4	Sustainability	35	247
5	Construction	32	237
6	Construction and demolition waste (CDW)	29	255
7	Management	23	191
8	Construction industry	21	188
9	Reuse	21	160
10	Design	21	144
11	Buildings	20	159
12	Model	18	149
13	Framework	16	140
14	Architectural design	16	121
15	Performance	15	91
16	Deconstruction	14	130
17	Concrete	14	126
18	Demolition	14	120
19	Recycling	14	113
20	Energy	14	101
21	Barriers	14	100
22	Carbon	13	120
23	Environmental impact	13	112
24	Indicator	13	102
25	Challenges	13	99
26	Supply chain	13	94
27	Built environment	13	84
28	Optimization	12	98
29	Waste management	12	94
30	Life cycle	12	92
31	Big data	12	91
32	Waste	12	91
33	Decision making	11	86
34	System	11	84
35	Circularity	10	65
36	Innovation	10	54

determining their practicality and the level of expertise required to use them. The scoring system for user-friendliness is as follows: computational plugins that are downloadable from a website but have no documentation are assigned 1 point, while those that have a website or paper describing the method are assigned 2 points. Tools that have more extensive documentation, such as a focused paper or tutorials, are assigned 3 points. BIM plugins are given 4 points since they don't require knowledge of visual scripting but still require a certain level of understanding of the BIM platform. Web-based tools are considered the most user-friendly and are assigned 5 points since they don't require prior knowledge of CAD or BIM and can be used by a variety of stakeholders. Additionally, reporting results is an important feature for practitioners, as it helps to reduce the time required to evaluate design alternatives and prepare project documentation.

Several studies have discussed the use of BIM models for LCA application and have focused on the level of development (LOD) of these models (Gomes et al., 2019; Morsi et al., 2022; Nilsen & Bohne, 2019; Tam et al., 2022). However, LODs predefine geometrical and non-geometrical information in a standardized nomenclature, which has been criticized as being disconnected from the actual purposes of information models in BIM. As a result, a new standard, the EN 17412-1:2020 'Level of Information Need' (LOIN) was developed by the European Committee for Standardization (CEN) (2020). LOIN provides a framework for defining the quality, quantity, and granularity of information requirements for a project, without predefining any information or geometry as in prior LOD formulations.

Table 6
Countries with the largest number of publications (i.e., at least 5 titles). The link strength is determined by the number of co-authored documents of a given country with another country. The total link strength is calculated in VOSviewer by summing up the link strengths that each item (i.e., the country in this case) has with other items in the network.

Country	Documents	Citations	Total link strength
United Kingdom	42	1006	37
China	35	640	30
Australia	27	437	24
Italy	24	129	12
Spain	22	203	13
United States	20	549	19
Germany	17	304	10
Netherlands	15	196	8
France	13	293	14
India	12	242	17
Canada	10	68	11
Brazil	9	54	4
Norway	8	130	6
Switzerland	8	107	14
Portugal	7	37	5
Taiwan	7	197	14
Denmark	6	84	5
Singapore	6	144	10
Austria	5	28	4
Iran	5	29	5
South Korea	5	154	8

4. Results

The following sections present the bibliometric analysis (Section 4.1) and a brief description of the digital tools reviewed (Section 4.2), followed by the evaluation across the selected criteria (Section 4.3). Fig. 3 shows the annual trend of publications and reveals that research interest in digital methods for a CE is increasing from 2017 onwards. Although not used as a search term, and beyond the focus of this study, Geographic Information Systems (GIS) methods and tools emerged in the bibliometric analysis (Göswein et al., 2019; Heisel et al., 2022; Honic et al., 2023; Schaubroeck et al., 2022).

4.1. Bibliometric analysis

In this section, we present network maps illustrating the co-occurrence of keywords (Fig. 4), and co-authorship between countries (Fig. 5). Additionally, the ranking of the most frequently used keywords is given in Table 5, as well as the list of countries with the largest number of publications in Table 6. For further exploration, we include additional network maps and tables in the Appendix, which depict co-authorship between authors, the co-citation of cited references, and bibliographic coupling of sources.

Although the term LCA was not used as a search term, it emerges as the third most used keyword after BIM and the two are in the same cluster (Fig. 4). The network map between countries shows that research in CE and digital methods has a global interest and collaboration networks.

4.2. CAD and computational design tools

The Food4Rhino database offers plugins for both Rhino and Grasshopper. Bombyx is a Grasshopper plugin developed for educational purposes at ETH Zürich in Switzerland with a database tailored towards the Swiss market (Basic et al., 2019). 'Cardinal LCA' is a Grasshopper (GH) plugin designed for non-experts to assess environmental impacts from an early design stage. 'One Click LCA' offers both a GH and a Rhino plugin for LCA described in a paper by Apellániz et al. (2021), and allows users to visualise the results in Rhino, and continue the evaluation process on its web platform. Additionally, 'EPiC for Grasshopper' a plugin developed by

Table 7
Comparison of One Click LCA and Tally plugins for Revit.

	One Click LCA	Tally
Type of solution and integration	Revit plugin; IFC, gbXML and Excel Spreadsheets imported into the web platform	Revit plugin
Databases	Generic databases or EPDs	custom database
Strengths	- availability of many databases for representative LCA data - completeness and plausibility checker of building data - built-in LCA rules for certifications/regulations - several types of visualisations for results	- integration with Revit's 'model categories' with LCA profiles - comparison of design models, assemblies, or a whole building model - reporting capability
Approach to comparing design alternatives	- import designs in the web-platform for editing and comparison - copy and modify baseline design in the web platform	- can use the 'design options' feature in Revit

the Melbourne School of Design, integrates the 'EPiC database', and enables users to create assemblies, and visualise charts of results in the Rhino viewport (Crawford et al., 2022a; Crawford et al., 2022b).

'Phoenix 3D' is a GH plugin that optimizes the spatial design of truss structures from new and reused components, aiming for minimum weight, LCA optimization, or maximizing component reuse (Structural Exploration Lab, n.d.). Warmuth et al. (2021) argued that computational workflows addressing the reuse of elements could further reduce environmental impacts in the design process. 'Rhino Circular' is a plugin developed by the Circular Construction Lab at Cornell University (Heisel & Nelson, 2020) that calculates the MCI at the building level and several C-indicators. Rhino Circular was recently made available in Food4Rhino in January 2023, along with a dataset of materials for calculating component circularity (Heisel et al., 2023). Custom materials and assemblies can be created in Rhino Circular, and a material passport of the material/assembly/building is visualised in real-time on the Rhino viewport. The Buildings and Habitats object Model (BHoM) is an open-source project initiated by Buro Happold (The BHoM, n.d.). It is designed to operate across various software environments and can facilitate the transfer of data across multiple software platforms. The BHoM offers an LCA toolkit that connects to generic LCA databases through open APIs and provides additional impact categories beyond GWP. BHoM also offers a user-interface for Grasshopper, Dynamo, and Microsoft Excel. Elshani et al. (2022, 2023) recently explored BHoM as a knowledge graph through semantic web technologies for multidisciplinary collaboration. As such, it provides a promising avenue for improving data interoperability between data sources and digital tools when evaluating circular design alternatives, and for assisting in decision-making during the design process.

The search on Dynamo packages returned only one relevant result, called 'LCA-Aeforos', dated 2015, that was not further analysed. It is worth noting another GH plugin called 'Swiftlet' that simplifies the connection to open APIs and can be useful for importing LCA data. As a result, it can facilitate creating custom workflows, without relying on the databases of GH plugins. Finally, Ladybug Tools is a popular GH plugin that is used for environmental analysis, daylight, and energy simulations (Sadeghipour Roudsari & Pak, 2013). Energy results with Ladybug can be used to calculate operational carbon emissions (Ladybug Tools, 2023). This workflow can also account for hourly carbon emissions intensities, thus accounting for when energy tends to be cleaner at times of low demand. While data for this workflow in Ladybug is for the US, it can be customized for other locations.

4.3. BIM plugins

Tally is a Revit plugin for building LCA that was initially developed by Kieran Timberlake and is now part of Building Transparency (2021, 2022), a non-profit organization. A free and open-access Revit version of Tally is available in beta which can export material quantities to EC3 (a free web-based tool) and evaluate the project with Environmental Product Declarations (EPD). One Click LCA, on the other hand, has developed plugins for both Revit and Rhino that allow importing the data to its web platform through IFC, gbXML, or an electronic spreadsheet. A detailed comparison of the Tally and One Click LCA plugins is given in Table 7. By assigning LCA profiles to BIM objects in a streamlined BIM-LCA integration, the time needed to generate results is greatly reduced. Wastiels & Decuypere (2019, p. 2) define an LCA profile as a "*set of LCA data for a certain material type or a combination of materials, either as a generic set of LCA data, an EPD, or a combination of both.*" However, the BIM-LCA approach carries the risk of errors that can arise from inaccuracies in the quantities extracted. Without a quality assurance process in place, such errors can undermine the reliability of LCA results. One Click LCA offers a feature for verifying the accuracy and completeness of building data to prevent such issues.

Circular EcoBIM, is a Revit plugin that supports the three steps of the EU Level(s) framework by calculating the GWP and building LCA for Level 1 (concept design) and Level 2 (detailed design and construction). It also offers a digital twin application for Level 3 (as built) and calculates a Building Circularity Indicator (BCI) based on the methodology developed by Cottafava & Ritzen (2021). The HBERT plugin for Revit provides calculations in line with EN 15978 utilizing the Inventory of Carbon and Energy (ICE) database (Jones & Hammond, 2019). 'Carbo Life Calculator' maps Revit materials by a closest match in material name to the LCA database, and allows to manually map materials, and to make changes in its database including the GWP emissions for each LCA module, thus enabling to use custom and reliable LCA data. Beacon, an open access Revit plugin by Thornton Tomasetti, is developed for structural engineers to calculate the embodied carbon of structures. As a result, Beacon has a limited application to Revit categories which are: structural framing, columns, foundations, walls, and floors. Beacon provides some default GWP coefficients from select industry EPDs in North America, where values can be changed by the user. In addition, the results can be compared to industry benchmark studies (Carbon Leadership Forum, 2017).

4.4. Comparison of features

Table 8 presents the comparison of digital tools. Notably, many of the reviewed tools are freely available to practitioners, with some tools utilizing publicly available databases or a custom-developed database. All reviewed tools provided information on their website or in published literature, but web-based parametric tools were generally found to be more user-friendly. Carbon Designer 3D, for instance, is a web-based parametric tool with 3D visualisation capabilities that allows for the creation of baseline buildings and using this data for filling in missing information in later project stages (One Click LCA, n.d.-a). It is worth noting that other parametric web-based tools are being developed for internal use in companies, such as Cactus (Webb Yates Engineers, 2023), while other tools, such as EHDD's EPIC, are available to the broader industry. EPIC by EHDD does not have a 3D interface but is used to provide early-stage benchmarks for WLC.

Out of the tools reviewed, only Rhino Circular and Circular EcoBIM have implemented C-indicators based on scientific methodologies using the MCI. One Click LCA includes a 'Building Circularity Index' that considers the use of recycled, reused, or renewable materials, disassembly, and end-of-life processes. However, the website lacks detailed information or citations regarding the methodology and calculations involved. Although Ladybug Tools does not have LCA or CE functionalities, it can still be used in early design workflows with other plugins to estimate the

Table 8
Comparison of digital tools and workflows.

Criteria ✓ yes (✓) partial x no	Beacon	BHoM	Bombyx	Cardinal LCA	Carbo Life Calc.	Circular EcoBIM	EPiC for GH	HBERT plugin	Ladybug Tools	OCL Carbon Designer 3D	One Click LCA (OCL)	Phoenix 3D	Rhino Circular	Tally
Type of tool	Revit plugin	GH, Dynamo, and Excel interfaces, and more software environments	GH plugin	GH plugin	Revit plugin	Revit plugin, Dynamo scripts	GH plugin	Revit plugin	GH plugin	Web-based tool	Rhino, GH, Revit + web tool	GH plugin	GH plugin	Revit plugin
Open Access	✓	✓	✓	✓	✓	(✓) Dynamo scripts	✓	✓	✓	x	x	✓	✓	(✓)
Database	industry EPDs, user-specified	ICE, EC3, Boverket, Ökobaudat, Quartz	Swiss LCA database (KBOB, 2016)	EC3, ICE	ICE, IstructE, EPDs, user-specified	Ökobaudat, EPDs, specific LCIs (Göswein et al., 2022)	EPiC database	ICE	N/A	Generic data by region	Generic and EPD global data	Swiss LCA database (KBOB, 2016)		Custom database
Enrich & align data schema e.g., with the IFC, bSDD definitions	x	x		x	x	x	x	x	x	x	x	x	x	x
User-friendliness	4	2	3	3	4	4	3	4	3	5	4	2	3	4
Report feature	(✓) charts	x	x	(✓) charts	(✓) heatmaps of CO_2, charts	✓ report	(✓) charts	(✓) charts	(✓) heatmaps, charts	✓ GHG results and charts	✓ report	(✓) visualisation of stock and new design, heatmaps of CO_2	✓ charts, material passports	✓ report
Operational carbon	x	x	(✓) through Hive plugin	x	x	x	x	x	✓	x	x	x	x	x
Early Carbon	(✓)	✓	✓	✓	(✓)	✓	✓	(✓)	x	✓	(✓)	(✓) truss structures	✓	✓
Embodied Carbon	✓	✓	✓	✓	✓	✓	✓	✓	x	✓	✓	(✓) truss structures	x	✓
Building LCA	x	✓	(✓)	x	x	✓	x	x	x	x	✓	x	x	✓
Circularity indicators	x	x	x	x	x	✓	x	x	x	x	✓ custom (building circularity index)	(✓) ratio new/reused elements, or by weight	✓	x
Other supported workflows or metrics	✓ compare to benchmarks	✓ data exchange between tools	✓ Can Include and report Biogenic carbon in LCA	x	x	LCC, digital twin	Embodied energy, embodied water	x	✓ daylight, energy, thermal comfort	x	LCC, templates for certification schemes & regulations	✓ algorithm for the design of trusses	x	✓Can include and report Biogenic carbon in LCA
Optimization methods and/or combine workflows	x	✓	✓	✓	x	(✓) in Dynamo	✓	x	✓	(✓)	(✓) in GH	✓	✓	x

building's WLC. For example, the Danish regulation requires WLC limits of 12 $kgCO_2/m^2$/year for new construction over 1,000 m^2 since 2023 (Birgisdóttir, 2021; Bygningsreglementets.dk, 2023). The reviewed GH plugins do not include an energy calculation module, except for Bombyx which can integrate such results from 'Hive', another GH plugin by ETH Zürich. Some of them focus solely on carbon footprint calculations. The same applies to reviewed BIM plugins like Beacon, Cabo Life Calculator and HBERT, where only Tally, One Click LCA, and Circular EcoBIM can calculate a building LCA and provide a report of results.

Partial alignment to the criteria in Table 8 is indicated in brackets (✓). Computational plugins can reference CAD/BIM models and combine tools, workflows, and optimization methods within the Rhino-GH, Revit-Dynamo, or between Revit and Rhino-GH with Rhino.Inside (Robert McNeel & Associates, 2021). This is not possible when using CAD/BIM plugins. One Click LCA's CAD plugin for Rhino relied solely on modelled 3D geometry to extract material quantities, which means that elements that are not explicitly modelled in Rhino, will be added manually in the web platform or through spreadsheets. When working with BIM, like in the case of Tally, the category (e.g., a wall, a floor, a door, a window) is used to assign LCA profiles of assemblies which allow selecting additional properties of elements that are not typically modelled in 3D. Circular EcoBIM, on the other hand, allows for a further type of BIM-LCA integration identified by Wastiels & Decuypere (2019) that had been envisioned in their study, but not implemented in tools at the time. This strategy consists of enriching BIM objects with information or referenced data in a database. In the case of Circular EcoBIM, LCA and disassembly data are added to BIM objects and used in a Dynamo workflow to calculate the BCI. This strategy has the potential for further enhancement by aligning data schemas in the BIM model with MPs, enriching the BIM model with relevant properties and values, and utilizing digital models to calculate indicators and evaluate circularity potential for reusing elements.

5. Discussion

In recent years, the importance of sustainable construction practices has grown significantly due to the need to reduce resource extraction, and waste generation, and mitigate the impacts of climate change. The bibliometric analysis reveals an expanding research landscape on the CE, characterized by interconnected clusters of keywords that overlap and interact. This finding may indicate the interdisciplinarity of the field and research in the construction industry. Waste management, BIM, LCA, and deconstruction have been the focus of several research studies, while interest in reuse, design, and circularity is emerging as indicated by the bibliometric analysis and recent articles. However, incorporating these principles into the design process can be challenging for architects and engineers, particularly when it comes to quantifying environmental impacts and the benefits of choices when implementing circular design strategies. To address these challenges, several digital tools have been developed by the research community, industry, and software companies. Through this review, the tools are evaluated based on their potential to facilitate a CE, using practical criteria for assessing environmental impacts and circular design strategies. This review highlights the potential of these tools to drive positive change, and their limitations, and suggests areas for future research and development.

5.1. Gaps in tools

Only a few BIM plugins currently offer complete 'building LCA' and reporting features. In contrast, computational plugins are more prevalent for Grasshopper than for Dynamo. This difference may be attributed to the focus of BIM plugins on leveraging BIM models for calculation and automation features, while computational plugins prioritize customizable workflows in Grasshopper. However, automation in the BIM environment often comes at the cost of reduced flexibility, as it may limit the utilization of parametric modelling capabilities and integration with other plugins' workflows. These findings align with the literature analysis which revealed the variety of approaches, where 26 articles employed computational methods, 87 discussed BIM, and 46 utilized a combination of methods (Fig. 1).

Computational plugins can facilitate evaluating circular design strategies such as the algorithmic design with Phoenix, circularity evaluation in Rhino Circular, or data exchange across platforms with BHoM. They also offer greater flexibility in the selection of the LCA database as compared to BIM plugins. However, it should be noted that open access plugins may not receive future releases, leading to potential incompatibility with newer software versions, or time-representativeness of LCA data, such as in the case of *Tortuga for GH* or *LCA-Aeforos* for Dynamo. While GH tools allow linking tools and exchanging data, none of the BIM plugins have aimed to extend and align data schemas with the IFC. Such a feature would be useful for exporting BIM models with LCA data for compliance with building permits and climate regulations. Third-party plugins, such as the IfcOpenShell are already leveraged through the BlenderBIM Add-on, which can read and edit IFC files. Some commercial Rhino plugins such as VisualARQ, GeometryGym, and BEAM can be used to read and export to the IFC (Asuni CAD, n.d.; GeometryGym, n.d.; MKS DTECH, n.d.).

Several C-indicators have been proposed in the literature, but these metrics remain underdeveloped in current tools, with only a few implementations like in Rhino Circular and Circular EcoBIM, which have created their custom databases for this purpose. As highlighted in the literature review (Section 2.2), complementary sustainability metrics should be used when evaluating circular strategies, such as LCA and LCC. Moreover, to compute circularity metrics, data on materials and products is required, either from a generic database or MPs/DPPs (Jansen et al., 2022; World Business Council for Sustainable Development, 2023). One example is the Madaster platform, which utilizes a generic material circularity database developed by Madaster, & EPEA GmbH (2023). Although C-indicators are still in an emerging phase, they have the potential to play a significant role in assessing CE strategies in buildings. However, more case studies are needed to demonstrate their practical application. In addition, the goal in building design and construction should not be to capture everything in one single metric, such as achieving a high level of material recirculation. Rather, metrics should complement other sustainability considerations, such as economic and social aspects, prioritize in-situ reuse of structures, ensure the quality of materials, and maximize reuse and value retention of building components before resorting to recycling or other forms of recovery.

Regarding regulations, One Click LCA is a tool that provides calculations aligned with the assessment methods of various countries on the web platform. Other tools, such as Tally and Circular EcoBIM provide assessments based on LCA standards (European Committee for Standardization, 2011; International Organization for Standardization 2006a, 2006b). However, as highlighted in previous research, LCA evaluations may still necessitate utilizing other software platforms and involving LCA experts, or the use of calculation spreadsheets for compliance with regulations (Potrč Obrecht et al., 2020).

The LOIN framework has not yet been utilized in recent studies or by plugins, despite its potential to contribute to more qualitative LCAs. A recent study utilizes the EN 17412-1:2020 LOIN standard and expands its applicability for the reuse of building elements (Dervishaj et al., 2023a). Their study proposed digital reuse guidelines by encompassing both geometrical and alphanumerical information aspects of LOIN. These guidelines can be used to model and share more reliable information, as well as for verifying the presence of required properties in BIM models, and for validating their reusability in new projects. Hence, LOIN can be a valuable framework to consider in CAD/BIM tools when modelling and requesting information in BIM, and more reliable LCA results. Another crucial aspect to consider is the choice of the database, which in the tools reviewed, may have been influenced by what database was available at the time, or the development of a custom database, as seen in the case of Circular EcoBIM. However, for compliance with regulations, it is essential to ensure that the data used is representative of the time and context.

5.2. Further development

The study highlights several gaps in the current state of digital tools and recommends future developments to address these gaps. For instance, the terms reuse, design (and architectural design), and concrete (i.e., the material) appeared frequently in the literature and were interconnected (see Table 5), but not yet as frequently as the term CDW. One area of focus can be the development of tools for circular design from reused building elements. Although the reuse of concrete has been shown in successful applications and is of interest to many ongoing research efforts in Europe (Devènes et al., 2023; Huuhka et al., 2024; Kuzminykh et al., 2023; Stenberg et al., 2022), it could be argued that digital methods and tools for the reuse of concrete have not been thoroughly explored. This is particularly important due to the large impact of emissions from concrete production, and the prevalence of structures made of precast concrete in many European countries (Huuhka et al., 2015). Various innovative approaches, such as algorithms that automate design through a stock of precast concrete elements, MPs, and digital twins of reused building elements, could facilitate the exchange of information for using buildings as material banks, designing for reuse, and conducting sustainability evaluations. A recent study delves into these aspects, specifically focusing on the role of tracking devices for the reuse of precast concrete elements (Dervishaj et al., 2023b). The tags can provide the connection between physical assets and their digital counterpart (i.e., the BIM model), towards the development of digital twins for building elements.

Computational tools offer higher flexibility, more workflows, metrics, and the possibility for parametric optimization. The ability to connect scripts to CAD/BIM models is particularly valuable because it enables the evaluation of multiple indicators for a comprehensive assessment of design alternatives. On the other hand, BIM tools provide complete LCAs and reporting, which is useful feedback for interpreting results for decision-making. To enhance consistency in reporting and comparability of studies, future studies and tools can use the LOIN guidelines to structure BIM models for improving information sharing and collaboration. Additionally, using classification systems, enriching BIM models through the bSDD, adopting a common taxonomy for LCA such as the one proposed by Rodriguez et al. (2019) and LCA ontologies (Ghose et al., 2022), and data templates in BIM following the ISO 22057 standard (International Organization for Standardization, 2022), can help produce more reliable models for digital building permits and environmental assessment. Hence, further development of BIM-LCA plugins could eliminate the need for dedicated LCA software or spreadsheets.

The study also recommends that tools need to integrate and make available more sources of data for LCA and C-indicators. Additionally, few recent papers explored new approaches for BIM-LCA using IFC (LLatas et al., 2022; Theißen et al., 2020), and LCA ontologies with semantic web technologies (Nguyen & Sharmak, 2021; Sobhkhiz et al., 2021). Further development could consist of using proposed LCA ontologies, to add, link and store information from BIM models, digital building logbooks and MPs in knowledge graphs. For example, the BHoM could be used in such cases as a knowledge graph, to support data exchange and integration, sharing of information, calculating LCAs and other relevant CE and sustainability aspects. These developments are of interest to facilitate the use of open standards and enhance collaboration, for instance when parties rely on different tools but need to exchange information. The exchange of data between CAD, BIM, computational plugins, web-based tools, and open access databases is of benefit for collaboration between stakeholders.

6. Conclusions

This paper presents a review and comparative analysis of the current state of digital tools used in the context of a CE in the built environment. The study aimed to identify plugins that can be used in the design process by practitioners. The introduction of the paper highlights the role of digital methods in facilitating the reduction of environmental impacts and promoting circularity in buildings, as these goals are embedded within regulatory frameworks and green building standards. The scientific literature and regulations rely on established methodologies like LCA for evaluating the environmental performance of buildings. In the methods section, the scope and delimitations of the study and relevant criteria for the comparison of tools are described. The findings of this study are supported by a bibliometric analysis, and we have identified which criteria are possible to evaluate through CAD, BIM, or computational plugins, and described the main features of each tool. In the discussion section, we highlight the gaps and present recommendations for further development.

We find that the analysed CE tools for digital design could be further developed to integrate more representative LCA data and align with the requirements of regulations. Circularity metrics remain underdeveloped in tools compared to the plethora of proposed C-indicators in the literature. Trade-offs in criteria were highlighted between more flexible computational design plugins and BIM-based tools. The study suggests that the CE opens new possibilities for exploration beyond LCA, such as design algorithms for structures, or linking digital twins and material passports for digital collaboration. Additionally, given the variety of digital tools, and methodological differences in LCAs, it remains challenging for practitioners to achieve CE objectives solely through digital workflows. Nevertheless, digital tools can help designers work towards these goals and evaluate circular design strategies more effectively. Digital technologies have the potential to support the sustainable transition of the construction sector. However, further developments are still needed for digital tools to allow for a comprehensive evaluation of environmental impacts, circularity, and other sustainability aspects.

Funding information

This paper presents research conducted as part of the *ReCreate project*, which received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 958200.

CRediT authorship contribution statement

Arlind Dervishaj: Conceptualization, Methodology, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Kjartan Gudmundsson:** Conceptualization, Methodology, Writing – review & editing, Funding acquisition.

Declaration of Competing Interest

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

Data availability

No data was used for the research described in the article.

Acknowledgements

We would like to express our gratitude to Tove Malmqvist, senior researcher at KTH, for reading our paper and providing valuable feedback. We would also like to thank the journal's reviewers for their insightful comments and suggestions.

Appendix

Fig. 6, Fig. 7, Table 9, Fig. 8, Table 10.

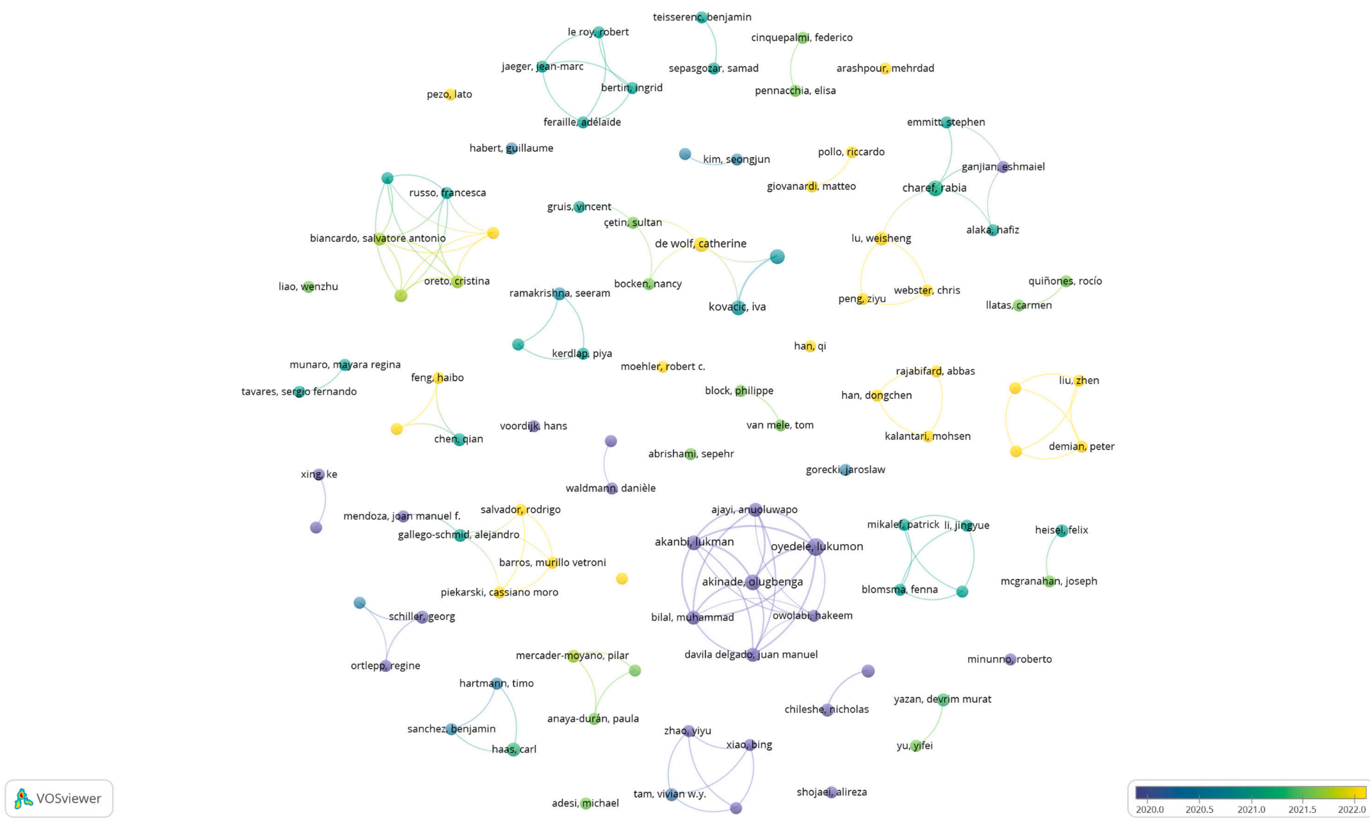

Fig. 6. Network map of co-authorship between authors in VOSviewer. Colours indicate the year of publication.

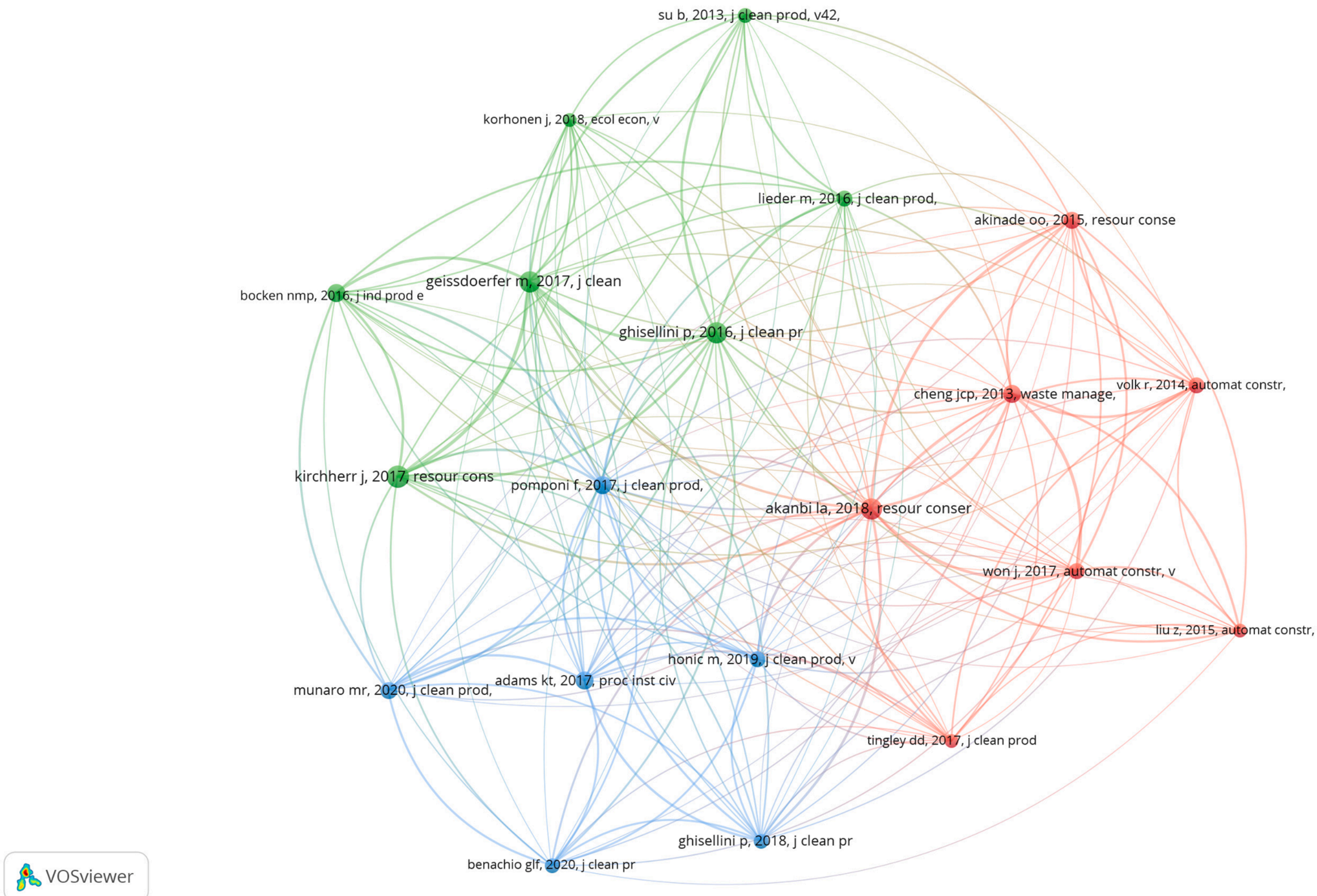

Fig. 7. Network map of top twenty cited references based on co-citation analysis in VOSviewer (i.e., the number of times cited together in the documents).

Table 9
List of top twenty cited references from the analysis in Fig. 7. It should be noted that the ranking of the cited references includes only the citations from the articles that were scoped in the bibliometric analysis.

Authors	Title	Journal	Citations	Total link strength
Adams et al. (2017)	Circular economy in construction: current awareness, challenges and enablers	Waste and Resource Management	20	59
Akanbi et al. (2018)	Salvaging building materials in a circular economy: A BIM-based whole-life performance estimator	Resources, Conservation and Recycling	29	104
Akinade et al. (2015)	Waste minimisation through deconstruction: A BIM based Deconstructability Assessment Score (BIM-DAS)	Resources, Conservation and Recycling	19	56
Benachio et al. (2020)	Circular economy in the construction industry: A systematic literature review	Journal of Cleaner Production	14	52
Bocken et al. (2016)	Product design and business model strategies for a circular economy	Journal of Industrial and Production Engineering	20	62
Cheng & Ma (2013)	A BIM-based system for demolition and renovation waste estimation and planning	Waste Management	20	72
Densley Tingley et al. (2017)	Understanding and overcoming the barriers to structural steel reuse, a UK perspective	Journal of Cleaner Production	13	47
Geissdoerfer et al. (2017)	The Circular Economy – A new sustainability paradigm?	Journal of Cleaner Production	29	85
Ghisellini et al. (2016)	A review on circular economy: the expected transition to a balanced interplay of environmental and economic systems	Journal of Cleaner Production	29	80
Ghisellini et al. (2018)	Exploring environmental and economic costs and benefits of a circular economy approach to the construction and demolition sector. A literature review	Journal of Cleaner Production	15	64
Honic et al. (2019)	Improving the recycling potential of buildings through Material Passports (MP): An Austrian case study	Journal of Cleaner Production	16	53

(continued on next page)

Table 9 (*continued*)

Authors	Title	Journal	Citations	Total link strength
Kirchherr et al. (2017)	Conceptualizing the circular economy: An analysis of 114 definitions	Resources, Conservation and Recycling	30	78
Korhonen et al. (2018)	Circular Economy: The Concept and its Limitations	Ecological Economics	13	36
Lieder & Rashid (2016)	Towards circular economy implementation: a comprehensive review in context of manufacturing industry	Journal of Cleaner Production	16	52
Liu et al. (2015)	A BIM-aided construction waste minimisation framework	Automation in Construction	13	39
Munaro et al. (2020)	Towards circular and more sustainable buildings: A systematic literature review on the circular economy in the built environment	Journal of Cleaner Production	18	56
Pomponi & Moncaster (2017)	Circular economy for the built environment: A research framework	Journal of Cleaner Production	20	75
Su et al. (2013)	A review of the circular economy in China: moving from rhetoric to implementation	Journal of Cleaner Production	15	40
Volk et al. (2014)	Building Information Modeling (BIM) for existing buildings — Literature review and future needs	Automation in Construction	17	48
Won & Cheng (2017)	Identifying potential opportunities of building information modeling for construction and demolition waste management and minimization	Automation in Construction	16	60

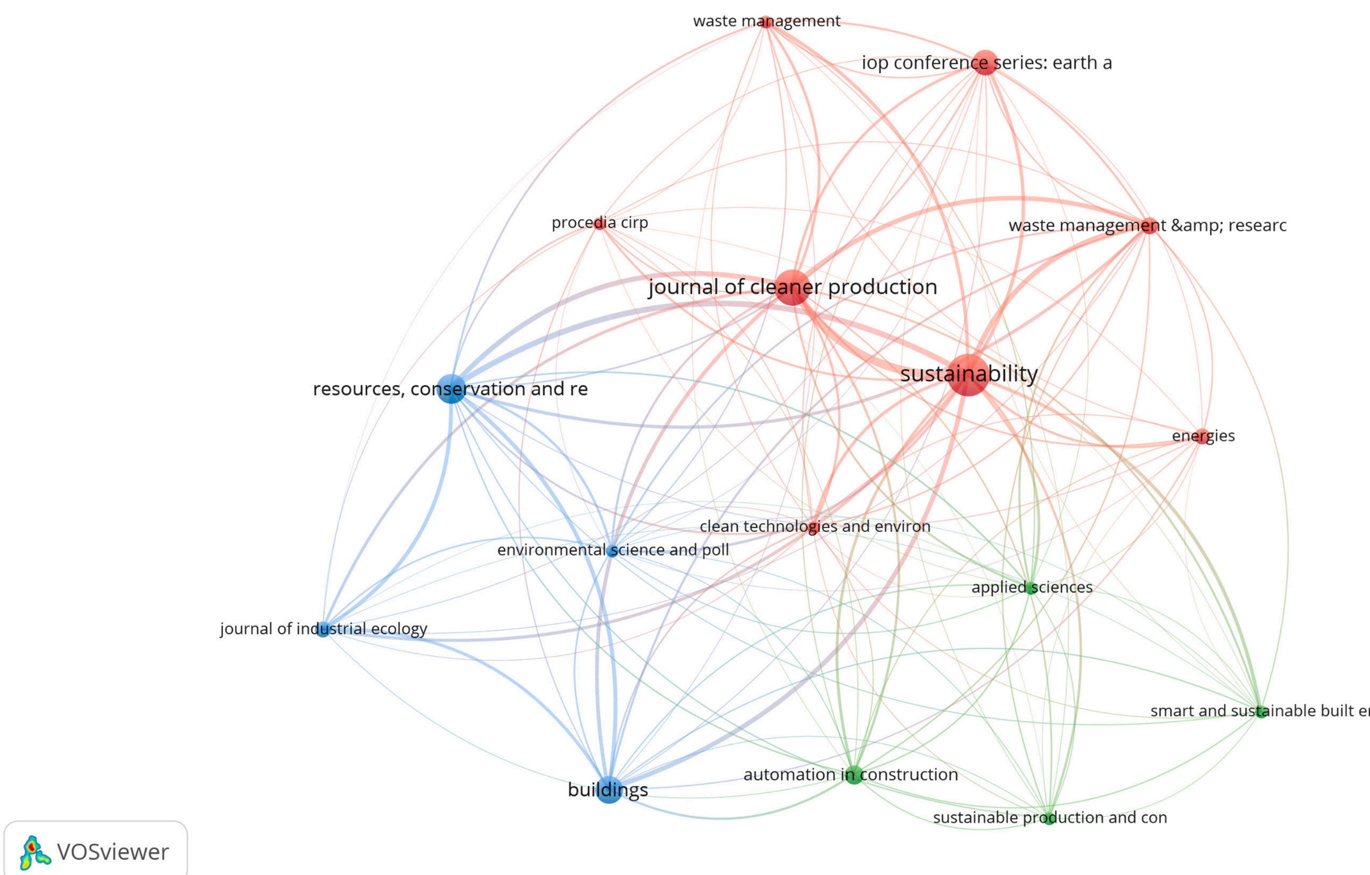

Fig. 8. Bibliographic coupling of sources (journal and conference articles). The links indicate that the sources are both cited by the same document.

Table 10
Sources of publications.

Source	Documents	Citations
Sustainability	25	343
Journal of Cleaner Production	19	574
Resources, Conservation and Recycling	13	623
Buildings	11	249
IOP Conference Series: Earth and Environmental Science	10	35
Automation in Construction	6	91
Waste Management & Research: The Journal for a Sustainable Circular Economy	5	20
Energies	4	38
Journal of Industrial Ecology	4	6

(*continued on next page*)

Table 10 (*continued*)

Source	Documents	Citations
Applied Sciences	3	30
Clean Technologies and Environmental Policy	3	71
Environmental Science and Pollution Research	3	2
Procedia CIRP	3	64
Smart and Sustainable Built Environment	3	11
Sustainable Production and Consumption	3	25
Waste Management	3	64

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