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2026-01-12

Deposited version:
Accepted Version

Peer-review status of attached file:
Peer-reviewed

Citation for published item:
Parece, S., Resende, R. & Rato, V. (2025). Current trends and challenges in BIM–LCA integration. In Leonor Marques Mano Domingos, Maria José Sousa (Ed.), Swarm Intelligence applications for the cities of the future. (pp. 187-218). Boca Raton: CRC Press.

Further information on publisher's website:
https://www.routledge.com/Swarm-Intelligence-Applications-for-the-Cities-of-the-Future/ManoDomingos-JoseSousa/p/book/9781032656755

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11 Current Trends and Challenges in BIM–LCA Integration

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1. Introduction

The Architecture, Engineering, Construction, and Operation (AECO) industry faces challenges that threaten its long-term sustainability, such as high greenhouse gas emissions and energy consumption, low productivity, and lack of technological evolution. The built environment accounts for 30–40% of global carbon dioxide emissions and 40% of global energy consumption (United Nations Environment Programme, 2024). European initiatives such as the Green Deal and the Renovation Wave emphasise reducing carbon dioxide emissions and achieving carbon neutrality by 2050 (Renovation Wave, 2024). These initiatives call for extensive

building renovation and rehabilitation, effective measures to reduce embodied and operational carbon footprints, and increased data digitalization throughout the lifecycle of buildings (Röck et al., 2020).

Life Cycle Assessment (LCA) is a widely accepted method for evaluating a building's environmental footprint throughout its life cycle. The ISO 14040 standard (ISO-14040, 2006) establishes a formal process for conducting an LCA of industrial processes. Unlike other industrial processes, which typically have limited elements with short lifespans and standard features, buildings have a wide range of elements with long lifespans and unique characteristics, so several LCA frameworks compatible with the construction industry have been proposed by EN 15978: 2011 and EN 15804: 2012. Building LCA involves multiplying all products, materials, and processes, which are usually compiled in a bill of quantities (BoQ), by environmental data cost from generic LCA databases or environmental product declarations (EPDs) (Cavalliere et al., 2019).

BIM (Building Informaion Modelling) digitally represents the physical and functional characteristics and information of construction projects, thereby simplifying LCA's data acquisition (Cheung et al., 2012). Detailed quantities can be extracted automatically, which speeds up the LCA calculations.

Numerous BIM-LCA integrations have been proposed in recent years. Still, there is no agreement on which approach is the most effective or accurate since this depends on the

design stage, the maturity of the information in BIM models, the BIM workflow implemented in the design company, and the overall goal of the LCA. Additionally, there is a gap between industry needs and academic research. Although studies have addressed the integrated use of BIM and LCA, they fail to identify the current stage of BIM-LCA technology and the main literature gaps.

This paper contributes to a systematic understanding of BIM-LCA integration identifying the current trends and challenges. The review covers academic articles on BIM-based LCA and commercial BIM-based LCA tools. The methodology for acquiring and categorizing the literature is detailed in Section 2. Section 3 summarizes and discusses the findings from the systematic literature review, while Section 4 presents the main conclusions.

2. Research Methods

Following the guidelines of the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) (Page et al., 2021), a systematic review was employed to explore BIM-based LCA applied in new buildings and renovation projects. This study aims to answer the research question: *What are the limitations, trends, and future developments of BIM-based LCA for building design?* The methodology involved systematic searching, screening, selection, and comprehensive reporting of pertinent literature. Two search strings were selected, targeting article titles, abstracts, and keywords across two journal databases, Scopus and Web of Science (WoS) (Table 1). Only peer-reviewed journal articles

in English from 2013– March 2024 were included, as they generally provide complete and high-quality information, while review articles, editorials, and conference papers were excluded. The search initially identified 749 publications. After removing 288 duplicates and applying the inclusion and exclusion criteria, 65 articles were selected (Figure 1).

Table 1 Search strings and results obtained.

Search strings	*Journal Database*	*Frequency of hits*	*Added to screening*
(“life cycle assessment” OR “life cycle environment* assessment” OR “life cycle analysis” OR “life cycle environment* analysis” OR “lifecycle assessment” OR “lifecycle analysis” OR LCA) AND (“building information model*” OR “BIM”)	Scopus	309	309
	WoS	252	86
(GWP OR “Global Warming Potential” OR “Carbon Footprint” OR “Embodied Carbon”) AND (“building information model*” OR “BIM”)	Scopus	108	48
	WoS	80	18

Search strings	*Journal Database*	*Frequency of hits*	*Added to screening*
Total		749	461

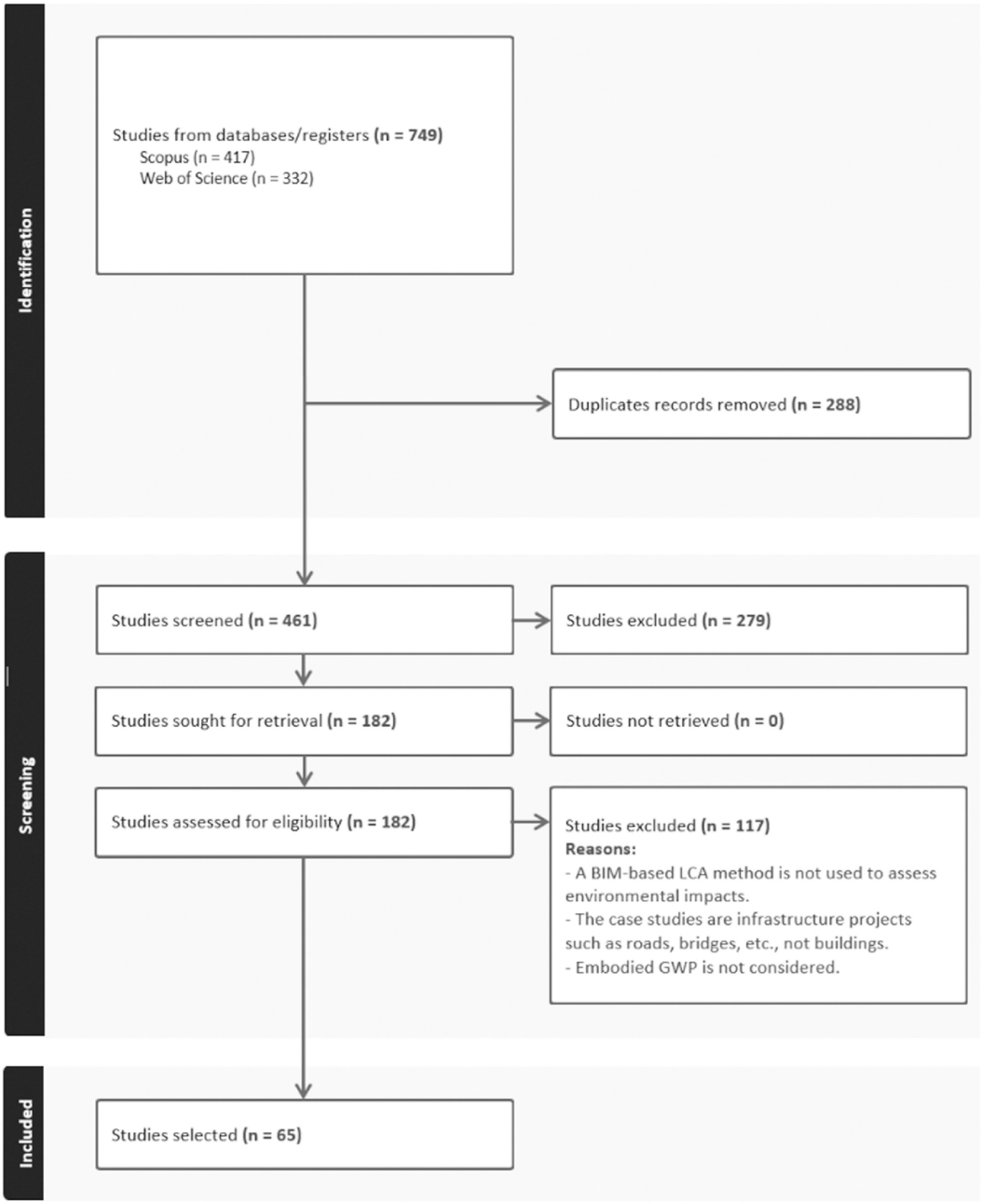


Fig. 1 Research framework

The screening process and selection of the 65 articles were guided by the following criteria:

- The article employs a BIM-based LCA integration to evaluate the environmental impact of new building construction, renovation, or refurbishment projects.
- The focus is on buildings, excluding infrastructure projects such as roads, bridges, and railways.
- The life-cycle concept includes considerations of Global Warming Potential (GWP) related to materials, also known as embodied carbon.

Furthermore, we aimed to highlight articles that addressed GWP and indicators such as life-cycle cost (LCC), design for disassembly (DfD), and design for adaptability (DfA), and articles that applied multi-criteria analysis (MCA) or multicriteria decision analysis (MCDA), optimisation techniques, and machine learning methods to improve decision-making.

3. Results and Discussion

In recent years, many articles on LCA integrated into BIM have been published with a growing trend. This field of research has been the focus of attention and rapid developments in particular over the last five years. Figure 2 demonstrates the 65 selected publications by year, from 2013 to March 2024.

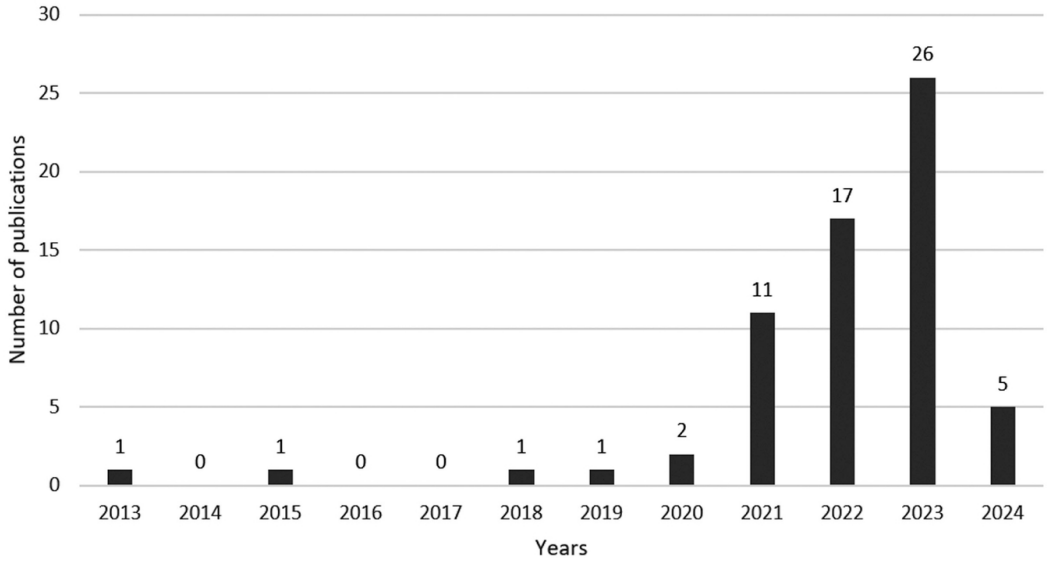


Fig. 2 Publications selected for full-text analysis by year.

Scientometric analysis was conducted using the VOSviewer software. VOSviewer is a tool for constructing and visualizing bibliometric networks (VOSviewer: Visualizing Scientific Landscapes, n.d.). Keywords serve as representative descriptions and directions of the research article's content. The minimum keyword frequency in VOSviewer was set to two. A filtering process followed, which involved merging synonyms (e.g., "carbon footprint" and "carbon emissions"), expanding abbreviated terms into their full forms (e.g., "BIM" to "building information modelling"), and excluding general terms. Twenty keywords were selected, as shown in Table 2 and Figure 3. A large node size signifies high frequency, a thick connection line denotes a strong relationship, and different colours categorise nodes into clusters. The results identified the five most prominent topics in the knowledge area of BIM-based LCA as life-cycle assessment, building information

modelling, environmental impacts, global warming potential, and sustainability. Figure 3 demonstrates a strong correlation between LCA and BIM keywords, indicating that BIM-based LCA is extensively utilised in the literature.

Table 2 Details of the keywords of the selected articles.

Keywords	*Occurrences*	*Total Link Strength*
building information modelling	42	93
life-cycle assessment	51	63
environmental impact	7	21
sustainability	7	21
global warming potential	7	19
life cycle cost	6	13
carbon footprint	5	8
embodied environmental impact	4	13
buildings	3	6
embodied carbon	3	9
energy consumption	3	1
level of development (loD)	3	9
decision-making	2	4
design process	2	8
embodied energy	2	4
multi-objective optimisation	2	5
optimisation	2	7

Keywords	*Occurrences*	*Total Link Strength*
RC structures	2	7
renovation	2	6
residential building	2	6

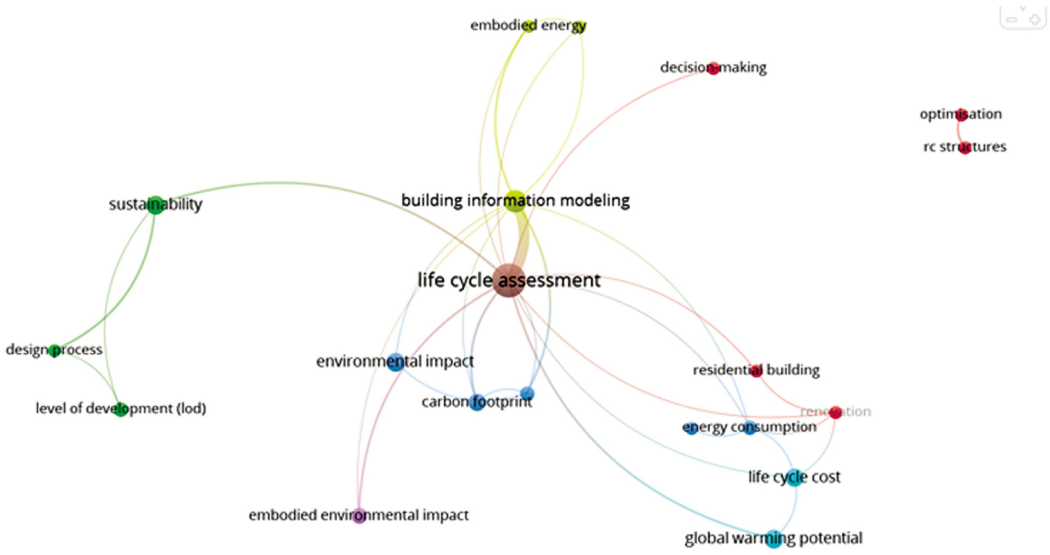


Fig. 3 Network of co-occurring keywords (Authors' own elaboration).

3.1 BIM Use

A BIM digitally represents buildings' physical and functional attributes. BIM offers numerous advantages, including enhanced visualisations, integration and relationship between data and geometry and, stakeholders' coordination. It is an valuable tool that significantly reduces the time and effort needed to manage building data. In the context of LCA, BIM enables the automated extraction of detailed quantities from models, facilitating the compilation of the life cycle inventory. Autodesk Revit (Architecture, Structures, and MEP) is the most common software for BIM-

based LCA, followed by Graphisoft ArchiCAD, as illustrated in Figure 4(a).

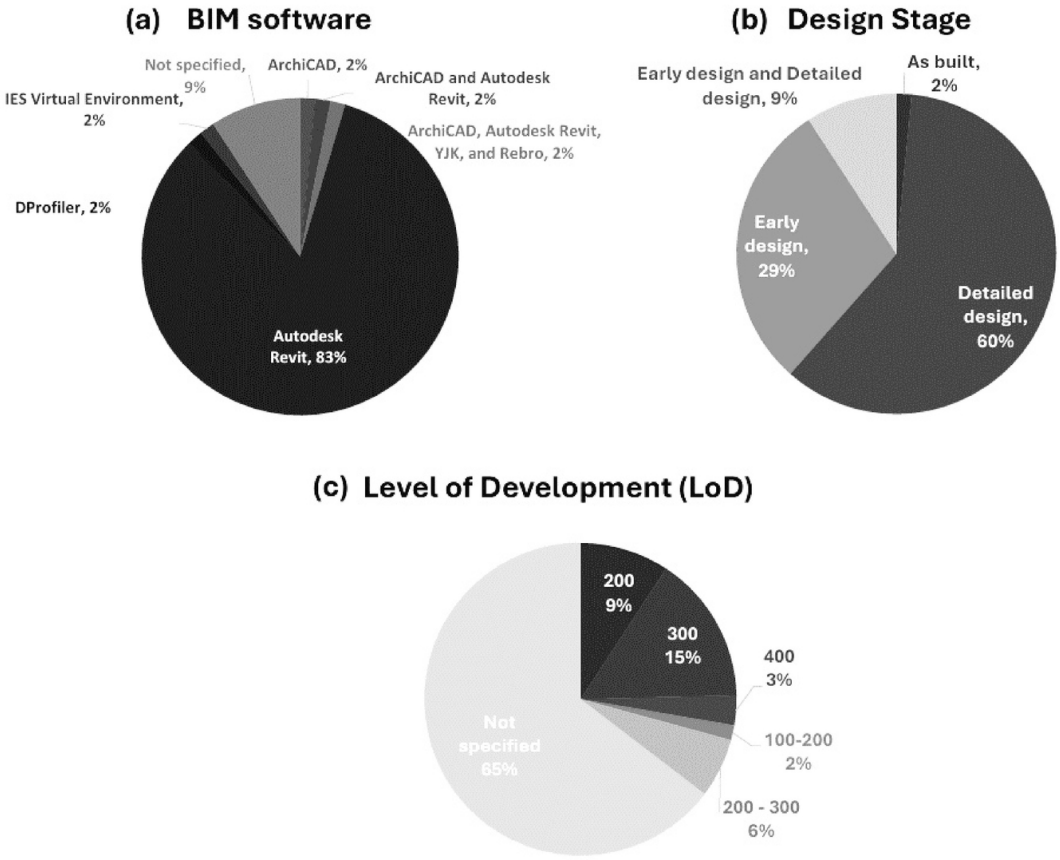


Fig. 4 Charts with the 65 case studies categorized by BIM software, design stage, and LoD.

The materials and components of a building are represented in a BIM model, both geometrically and non-geometrically. Their representation varies based on the Level of Development (LoD), defined by the American Institute of Architects as “the minimum dimensional, spatial, quantitative, qualitative, and other data included in a Model Element.” LoD is categorized into five levels, ranging from 100 to 500. Although the term “Level of Development” has been largely replaced by “Level of Information Need” (LoIN),

the majority of the articles analyzed still reference LoD (AIA, 2013).

Conducting an Building LCA in the early stages of the project is challenging. At this point of the design, it is inefficient to model with a high LoD, so designers rely on simplifications or adaptations in geometry and information. If these are not applied correctly, they can compromise the accuracy of the QtO and LCA results, potentially leading to incorrect decisions. Nonetheless, it is during this phase that project decisions are most impactful and least expensive to modify.

Additionally, we must consider heterogeneity in model creation, as models are not developed simultaneously across all specialities. As a general rule, LoD increases gradually to meet the demands of each design phase, but that is not always the case. For example, structural elements or external wall composition can be detailed early in the process, whereas interior finishes only later during execution. In this study, we follow the division of the building design process into three stages: early design stages, detailed design stages, and construction design stages, as in Sharif and Hammad (2019) and Zhou, Ma, et al. (2023).

While most articles did not specify the LoD (as shown in Figure 4 (c)), 10 articles identified LoD 300 as appropriate for accurate LCC and LCA calculations: (Alwan et al., 2021; Arvizu-Piña et al., 2023; Cheng et al., 2022; Kim and Kim, 2023; Lee et al., 2021; Llatas et al., 2022; Ma et al., 2024;

Nehasilová et al., 2022; Su et al., 2021; Zhang et al., 2022). At LoD 300, key materials and components are specified, including the actual sizes, shapes, locations, wall layers, and structural elements. Six works performed a simplified LCA study with LoD 200 BIM models: (Ajayi et al., 2015; Forth, Abualdenien, et al., 2023; Forth, Hollberg, et al., 2023; LLatas et al., 2022; Sobhkhiz et al., 2021; Soust-Verdaguer, Gutiérrez Moreno, et al., 2023).

Furthermore, 19 articles focus on early design LCA studies, while 39 aim for highly refined design phases (as shown in Figure 4 (b). The use of different tools for each design phase hinders a continuous and accurate LCA. Additionally, using various databases and methodologies can significantly alter the results. We have identified a lack of tools that allow environmental impacts to be monitored throughout the project (Bueno et al., 2018). As suggested by Cavalliere et al. (2019) these tools should utilise LCA databases ranging from generic data to Environmental Product Declarations (EPD), aligning the LoD with the design phase. Hollberg et al. (2020) continuously monitored GWP during the design phase and concluded that is often significantly overestimated in the early design stage due to model simplifications. Parece, Resende, et al. (2024) proposed a method adapted to different modelling techniques, LoD and design phases, which involves using a database of possible constructive solutions with maximum and minimum GWP values to complement the absolute quantities of the BIM objects in the model.

3.2 LCA Calculation

The International Standards Organization (ISO) and the CEN/TC 350 committee have developed comprehensive standards to assess environmental lifecycle impacts in construction projects. These standards cover the general framework, principles, calculation methods, lifecycle stages, impact categories and EPDs. While ISO 14040: 2006 is applicable across all sectors, other standards, such as ISO 15392: 2019, ISO 21678: 2020, EN 15978: 2011, and EN 15804: 2012, specifically address the use of LCA in construction activities. Together, these international standards encompass the essential components needed to conduct an LCA study for construction projects.

According to ISO 14040 and ISO 14044, LCA is divided into four steps: (1) Goal and scope definition: defining the goal, scope, and boundary of the LCA research; (2) Life cycle inventory: collecting data on products, materials, processes, and energy consumption to create an input or output inventory; (3) Life cycle impact assessment (LCIA): measuring flows, to determine an overall impact category total; and (4) Interpretation: evaluating the results from the life-cycle inventory and LCIA to draw conclusions and make recommendations.

The extensive range of impact categories in standard LCIA techniques adds complexity to LCA outcomes. Using a single score indicator can simplify decision-making while reducing the relevant information. For example, the CML-IA approach includes 10 impact categories, the ReCiPe 2016 Midpoint

method includes 18, and the TRACI 2.1 method includes ten. Reporting conventions for impact categories vary, so the closest match within the TRACI 2.1 methodology was used in Table 3. For instance, “life cycle carbon emissions” were generalized as GWP.

Table 3 Sixty-five publications categorized ac

References	*LCA Calculation Standard*	*LCA Database*	*LCA Application*	*Enviror Imp Indic*
(Zhou, Tam, et al., 2023a)	ISO 14040, ISO 14044	GaBi2018 database	Simplified	TRACI 2
(Zhou, Tam, et al„ 2023b)	ISO 14040, ISO 14044	GaBi2018 database	Simplified	TRACI 2
(Bueno and Fabricio, 2018)	ISO 14040, ILCD Flandbook	GaBi2018 database	Simplified	TRACI 2
(Sharif and Hammad, 2019)	Not specified	Bath ICE and Athena database	Simplified	GWP
(Taher and Elbeltagi, 2023)	ISO 14040	Ecoinvent database	Simplified	Eco metho
(Llatas et al., 2022)	ISO 14040	Not specified	Screening	GWP
(Abbasi and Noorzai, 2021)	EN 15978	Athena database	Simplified	TRACI 2
(Abdelaal et al., 2023)	EN 15978	OneClick LCA database	Screening	GWP, AP, EP,

References	*LCA Calculation Standard*	*LCA Database*	*LCA Application*	*Environ Imp Indic*
(Sobhkhiz et al., 2021)	ISO 14040, ISO 14044	Not specified	Screening	GWP
(Abouhamad and Abu-Hamd, 2020)	ISO 14040 and EN 15978.	Athena database	Simplified	USEPA
(Falegari and Shirzadi Javid, 2022)	ISO 14040 and EN 15978.	OneClick LCA database	Screening	GWP, AP, EP
(Su et al., 2021)	ISO 14040, ISO 14044	CLCD (Chinese Life Cycle Database)	Screening	GWP, RD
(Tushar, Bhuiyan, et al., 2022)	ISO 14040, ISO 14044	GaBi 2018 database	Simplified	GWP, AP, EI PED, RED
(Lu and Deng, 2023)	ISO 21931–1	Ökobaudat Database	Simplified	GWP
(Santos et al., 2020)	EN 15978	Not specified	Complete	CML 2(
(Cheng et al., 2022)	ISO 14040, EN 15978	Not specified	Simplified	GWP, MRD, POCP,
(Ajayi et al., 2015)	ISO 14040, EN 15978	Athena database	Simplified	GWP, H

References	*LCA Calculation Standard*	*LCA Database*	*LCA Application*	*Environ Imp Indic*
(Ma et al., 2024)	ISO 14040, ISO 14044, ISO 21930, ISO 21931, EN 15804, EN 15978	GaBi2018 database	Simplified	GWP, SF, PED,NF
(Jafari et al., 2024)	ISO 14040, EN 15978	Ecoinvent database	Simplified	ReCiPe
(Gao et al., 2024)	ISO 14040	eFootprint database	Simplified	GWP
(Chen and Gallardo, 2023)	ISO 14040, EN 15978	GaBi 2018 database and EPDs	Simplified	TRACI 2
(Greer et al., 2024)	ISO 14040, EN 15978	GaBi 2018 database	Simplified	GWP, ODP, PED, PEDr
(Forastiere et al., 2023)	EN 15978	GaBi and Ecoinvent databases	Simplified	GWP
(Basbagill et al., 2013)	EN 15978, GBT 51366–2019	Ecoinvent and Athena datadases	Simplified	GWP

References	*LCA Calculation Standard*	*LCA Database*	*LCA Application*	*Environ Imp Indic*
(LLatas et al., 2022)	IS021931–2JS0 14040, EN 15978	Ecoinvent v3.7.1 and the Spanish BEDEC	Screening	GWP
(Soust-Verdaguer, Gutiérrez Moreno, et al., 2023)	IS021931–2JS0 14040, EN 15978	Ecoinvent v3.7.1 and the Spanish BEDEC	Screening	GWP
(Soust-Verdaguer, Gutiérrez, et al., 2023)	ISO 21931-2, ISO 14040, EN 15978	Eco invent v3.7.1 and the Spanish BEDEC	Screening	GWP
(Ayman Mohamed et al., 2023)	EN 15643	ICE database and EPDs	Simplified	GWP
(Heydari and Heravi, 2023)	Not mentioned	ICE database and EPDs	Simplified	GWP
(Fenz et al., 2023)	EN 15978	Okobaudat database	Simplified	GWR A ADPE, ADPF, I

References	*LCA Calculation Standard*	*LCA Database*	*LCA Application*	*Environ Imp Indic*
(Hunt and Osorio-Sandoval, 2023)	NS	ICE database	Screening	GWP
(Serrano-Baena et al., 2023)	EN 15804, SO_15804	ECO-Platform (EPD), Construction Price Generator	Screening	GWP, E
(Shibata et al., 2023)	EN 15978 and RICS	OneC lick LCA database	Screening	GWP
(Boje et al., 2023)	EN 15978	Ecoinvent database, PSILCA 1.0 database	Simplified	EF v3.0
(Arvizu-Piña et al., 2023)	EN 15978	Mexican uh and EPDs	Screening	GWP, ODP, A POCP
(Forth, Hollberg, et al., 2023)	Not mentioned	Ökobaudat database	Simplified	GWP

References	*LCA Calculation Standard*	*LCA Database*	*LCA Application*	*Environ Imp Indic*
(Forth, Abualdenien, et al., 2023)	ISO 14040, EN 15643-2	Ökobaudat database	Simplified	GV
(Schneider-Marin et al., 2022)	ISO 14040, EN 15804, EN 15978	Ökobaudat database	Simplified	GWP
(Mowafy et al., 2023)	ISO 14040, EN 15804, EN 15978	KBOB database	Simplified	GWP
(Newberry et al., 2023)	ISO 14040 and EN 15978.	OneClick LCA database	Simplified	GWP
(Atashbar and Noorzai, 2023)	ISO 14040 and EN 15978.	Athena database	Simplified	GWP, P
(Deng and Lu, 2023)	ISO 14040 and EN 15978.	CEF database	Simplified	GWP
(Hansen et al., 2023; Kim and Kim, 2023)	EN 15978	Ökobaudat database	Simplified	GWP
(Kim and Kim, 2023)	EN 15804	EPDs, KICT	Simplified	GWP

References	*LCA Calculation Standard*	*LCA Database*	*LCA Application*	*Environ Imp Indic*
(Carvalho et al., 2023)	Not specified	Not specified	Simplified	GWP, AP, PO FFDP
(Morsi et al., 2022)	EN 15978, EN 15804, ISO 21931-1, ISO 21929-1, and ISO 14040	OneClick LCA database	Simplified	GWP, ODP, PED
(Nehaslová et al., 2022)	EN 15978, EN 15804, ISO 21931-1, ISO 21929-1, and ISO 14040	Eco invent database	Simplified	GWP, ODP, PED
(Tushar, Zhang, et al., 2022)	ISO 14040, ISO 14044	Ecoinvent 3.8 database	Simplified	GWP, ODP, PED, RED
(Zhang et al., 2022)	ISO 14040, ISO 14044	CLCD (Chinese Life Cycle Database)	Simplified	GWP

References	*LCA Calculation Standard*	*LCA Database*	*LCA Application*	*Environ Imp Indic*
(Besana and Tirelli, 2022)	EN 15978	OneClick LCA database	Simplified	GWP
(Motalebi et al., 2022)	EN 15978	Ecoinvent 3.8 database	Simplified	GWP, SFP, NR
(Xu et al., 2022)	ISO 14044, PAS 2050, EN 15978	SimaPro databases	Simplified	GWP
(Dauletbek and Zhou, 2022)	EN 15978	Ecoinvent 3.8 database	Simplified	GWP, SFP, NR
(Najjar et al., 2022)	ISO 14040, ISO 14044	Ecoinvent database	Simplified	IMPACT 2002+ ILCD 2(
(Alwan and Ilhan Jones, 2022)	EN 15978	ICE database	Simplified	GWP
(Filho et al., 2022)	EN 15978	GaBi 2018 database	Simplified	GWP, ODP, SFP, PE
(Soust-Verdaguer et	EN 15978	BEDEC database	Simplified	GWP

References	*LCA Calculation Standard*	*LCA Database*	*LCA Application*	*Environ Imp Indic*
al., 2022)				
(Martínez-Rocamora et al., 2021)	EN 15978	GaBi 2018 database	Simplified	GWP, ODP, PED, RED
(Figueiredo et al., 2021)	ISO 14040, ISO 14044	GaBi 2018 database	Simplified	GWP, A
(Ansah et al., 2021)	ISO 14040, ISO 14044	Ecoinvent database	Simplified	GWP, ODP, HTP, TETP, F
(Alwan et al., 2021)	ISO 14040, EN 15978	ICE database	Simplified	GWP
(Lee et al., 2021)	ISO 14040, ISO 14044	EPDs	Simplified	GWP, ODP, PDCP
(Uddin et al., 2021)	Not specified	ICE database	Simplified	GWP
(Carvalho et al., 2021)	EN 15978	Ecoinvent database	Simplified	GWP, ODP, POCP,
(Tushar et al., 2021a)	Not specified	GaBi 2018 database	Simplified	GWP, ODP,

References	*LCA Calculation Standard*	*LCA Database*	*LCA Application*	*Environ Imp Indic*
				PED, RED

Some studies focus on a single environmental indicator such as GWP (42%), for example, Llatas et al. (2022), Gao et al. (2024), Lu and Deng (2023); while others cover multiple environmental impact indicators (58%) (Zhou, Tam, et al., 2023a; Zhou, Tam, et al., 2023b; Bueno and Fabricio, 2018; (Abbasi and Noorzai, 2021), such as acidification potential (AP), eutrophication potential (EP), ozone depletion potential (ODP), smog formation potential (SFP), photochemical oxidant creation potential (POCP), abiotic depletion potential—elements (ADPE), abiotic depletion potential—fossil fuels (ADPF), primary energy demand (PED), primary non-renewable energy demand (PEDnr), and primary renewable energy demand (PEDr).

The *EeBGuide Handbook* delineates three tiers of comprehensive Building LCA: (1) Screening LCA, which constitutes a basic estimation involving simplified input and output data considering a few environmental impact indicators; (2) Simplified LCA, which employs specialised software tools such as Athena Impact Estimator; and (3) Complete LCA, an advanced analysis using advanced LCA software such as Simapro (Soust-Verdaguer et al., 2017). In

this review, 12 articles prepared a Screening LCA, and 52 articles a Simplified LCA (Table 3).

EN 15978:2011 categorises four building life-cycle stages: product and construction (A1–A5), use (B1–B5), end-of-life (C1–C4), and benefits and loads beyond the system boundary (D). The selected stages are still highly related to the goal and scope of the study. Most articles focused on the production and construction phase (A, 92%). Other phases included were the use (B, 72%),the end-of-life (C, 70%), and benefits and loads beyond the system boundary (D, 40%) (Table 3).

Most references use common LCA databases, such as GaBi (Zhou Tam, et al., 2023a; Ma et al., 2024), Athena; the Inventory of Carbon and Energy (ICE) (Sharif and Hammad, 2019); Ecoinvent (Heydari and Heravi 2023), while others adopted a local database, such as the Ökobaudat (Forth, Hollberg, et al., 2023), and (Forth, Abualdenien, et al. 2023), or the Chinese Life Cycle Inventory Database (Zhang et al., 2022).

Furthermore, 40% of the publications do not consider indicators in addition to those set out in the LCA, such as design for disassembly (DfD) and adaptability (DfA), life-cycle cost (LCC), social cost, or waste production and management. Examples of studies that take these additional indicators into account include Lu et al. (2023), who proposed a method based on OpenBIM to calculate the social

cost of carbon through the building life cycle; Santos et al. (2020), who developed a method to integrate BIM with LCA and LCC, incorporating environmental, economic, and physical information into BIM objects; Llattas et.al. (2022), who proposed a method to identify the design solution with the lowest CO2 emissions, the lowest cost, and the most beneficial impact on local employment; Fenz et al. (2023), who developed a web-based tool to assess the performance of renovation scenarios in terms of energy efficiency, LCA, LCC, and urban planning key performance indicators related to social well-being; Serrano-Baena et al. (2023), who developed a BIM-based software designed to assess the total economic cost, GWP, embodied energy, and waste mass; and, Kim et al. (2023), who proposed an LCA-based LCA-DfD method to quantitatively calculate environmental loads based on various design and deconstruction scenarios.

There is, therefore, a lack of tools to assess how circular economy principles such as DfD, waste management, and DfA influence LCA results. DfD and waste management enable the reuse of components, products, and materials, affecting the end-of-life (C) and benefits and loads beyond the system boundary (D) stages, and DfA extends the useful lifespan of the building by easily adapting it to future functional and user requirements.

3.3 BIM-LCA Integration

According to Zheng et al. (2023), the classification of BIM-LCA integration can be broadly categorised according to

three principles: data exchange, data extraction, and data flow. Safari and AzariJafari (2021) defined three categories for data exchange processes between BIM and LCA tools: conventional, static, and dynamic. In the conventional method, the bill of quantities or materials is extracted from the BIM model, typically as an Excel or CSV file. The collected data is then entered manually into the LCA software. In the static approach, the BIM model is converted into an IFC file and imported into the LCA software. This method utilizes the information delivery specifications (IDS) of BIM objects (BuildingSMART International, n.d.) for data sharing, which simplifies model updates and eliminates the need to recombine environmental information for each material or product. The dynamic approach allows calculations to be performed directly within the BIM environment using add-ons, facilitating an iterative design process.

Soust-Verdaguer et al. (2017) and Wastiels and Decuypere (2019) identified five distinct types of data flow: (a) export the BoQ from the BIM tool to LCA tools, as followed by Simba Pro, eFootprint LCA, OneClick LCA, Athena Impact Estimator, Athena Eco calculator, LCAbyg, OpenLCA (Table 4 (b)) export BIM models in IFC format and then load them into the LCA tool and align them with an established LCA data; (c) use a BIM viewer to handle data and then transfer it to an LCA software; (d) employ plug-ins that enable LCA analysis within the BIM application, such as the Autodesk Tally, Bombyx, Revit Dynamo scripts; (e) embed LCA

information directly into the BIM objects, as suggested by Santos et al. (2020).

Table 4 Characterisation of the LCA softwar

LCA Software	*Type of Software*	*Regionality*	*Database*	*New Data in the Databas*
Bombyx	Grasshopper add-on	KBOB database	Swiss LCA database	Yes
Athena Impact Estimator	Third-party dedicated LCA tool	North America	Athena database and EPDs	No
Athena Eco calculator	Third-party dedicated LCA tool	North America	Athena database and EPDs	No

LCA Software	*Type of Software*	*Regionality*	*Database*	*New Data in the Databas*
Autodesk Tally	Autodesk Revit add-on	North America	GaBi 2018 database and EPDs	No

LCA Software	*Type of Software*	*Regionality*	*Database*	*New Data in the Databas*
eFootprint LCA	Third-party dedicated LCA tool	China	CLCD-China	No
LCAbyg	Third-party dedicated LCA tool	Denmark	Okobaudat database	No
OneClick LCA	Third-party dedicated LCA tool and	North and South America,	Multiple databases	No

LCA Software	*Type of Software*	*Regionality*	*Database*	*New Data in the Databas*
	an add-on to export data from Revit	Europe, Middle East, Asia		
Open LCA	Third-party dedicated LCA tool	Germany	Multiple databases	No
Python script Brightway2 libraries	Python script	Luxembourg	Ecoinvent database, PSILCA 1.0 database	No

LCA Software	*Type of Software*	*Regionality*	*Database*	*New Data in the Databas*
Sima Pro	Third-party dedicated LCA tool	Netherlands	Multiple databases	Yes
eBalance	Third-party dedicated LCA tool	China	Multiple databases	No
Tool from (LLatas et al., 2022)	Dynamo script	Spain	Ecoinvent database	No

LCA Software	*Type of Software*	*Regionality*	*Database*	*New Data in the Databas*
WEB1ca	Third-party dedicated LCA tool	China	Chinese Life Cycle Inventory Database	No
Tools developed the authors	varies	varies	varies	varies

The LCA tools were categorized into the five categories mentioned above, and it was found that 60% of the references studied are third-party LCA tools, 23% are add-ons to BIM software, mostly Revit, 9% involve parametric modelling, such as Dynamo or Grasshopper scripts, and 8% feature LCA embedded in BIM objects, where the environmental information is parameterized in the BIM objects before calculation.

About data exchange, we found that 40% of the tools use conventional data exchange methods, 38% use dynamic data exchange, and 22% use static data exchange (Figure 5). Additionally, in 89% of the proposed methods, the correspondence between environmental data and the BoQ is carried out manually. Only 5% use an Excel sheet with the

Family and Type names corresponding to the LCA values (Alwan et al., 2021; Ansah et al., 2021; Carvalho et al., 2021), and 3% use an automatic learning algorithm, such as Natural Language Processing, to establish this correspondence automatically with good precision (Forth, Abualdenien, et al., 2023; Forth, Hollberg, et al., 2023), and 2% use the construction classification system to link the elements classified in the BoQ (Parece, Resende, et al., 2024) (Table 4).

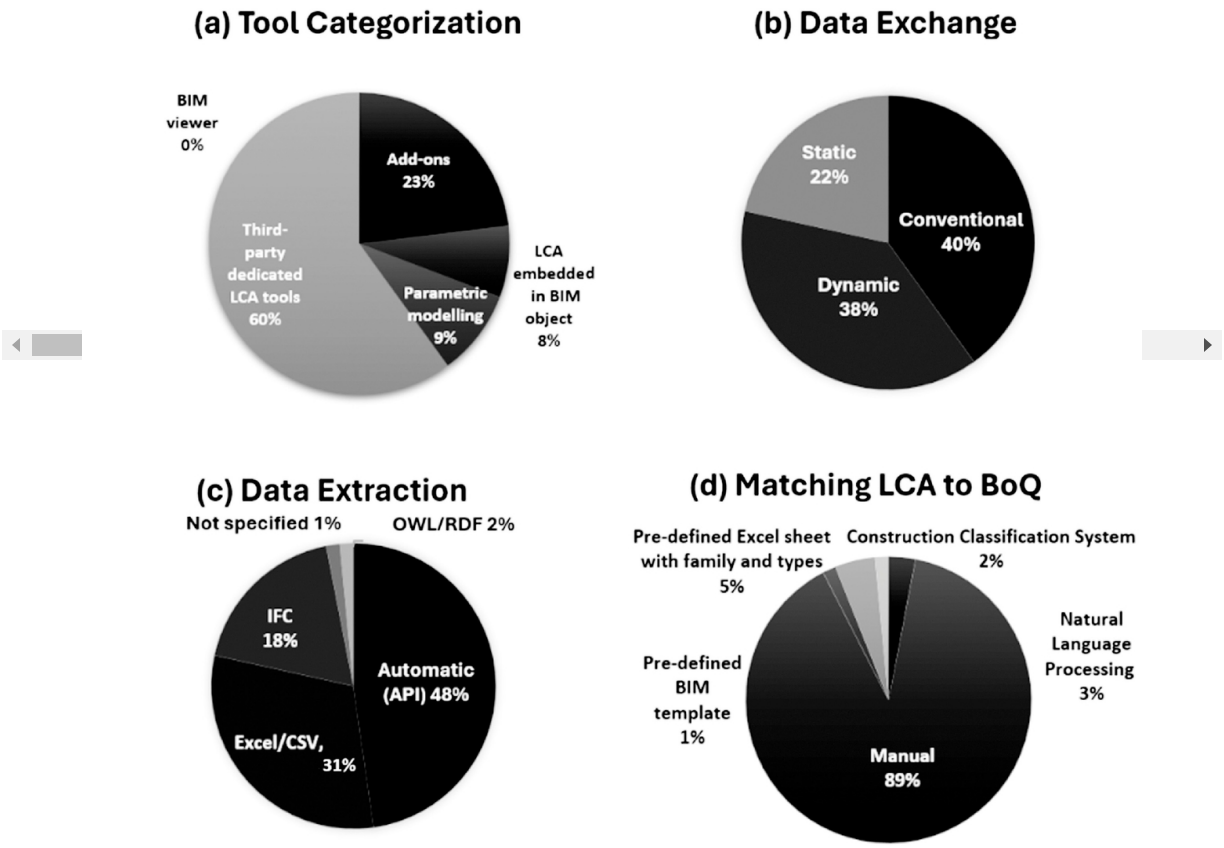


Fig. 5 Graphs with the 65 publications categorised by LCA tool, data exchange, data extraction and correspondence between LCA and BoQ.

3.4 Case study Application

Most publications selected an entire building as the functional unit for developing the LCA, although some only considered part of it (Tushar, Bhuiyan, et al., 2022, Bueno and Fabricio, 2018; Jafari et al., 2024). Concerning building properties, 37% focused on multi-residential buildings, 18% on single-dwellings and 9% on office buildings. Furthermore, 85% of the articles focused on new-build projects, while only 14% focused on renovation projects (Figure 6).

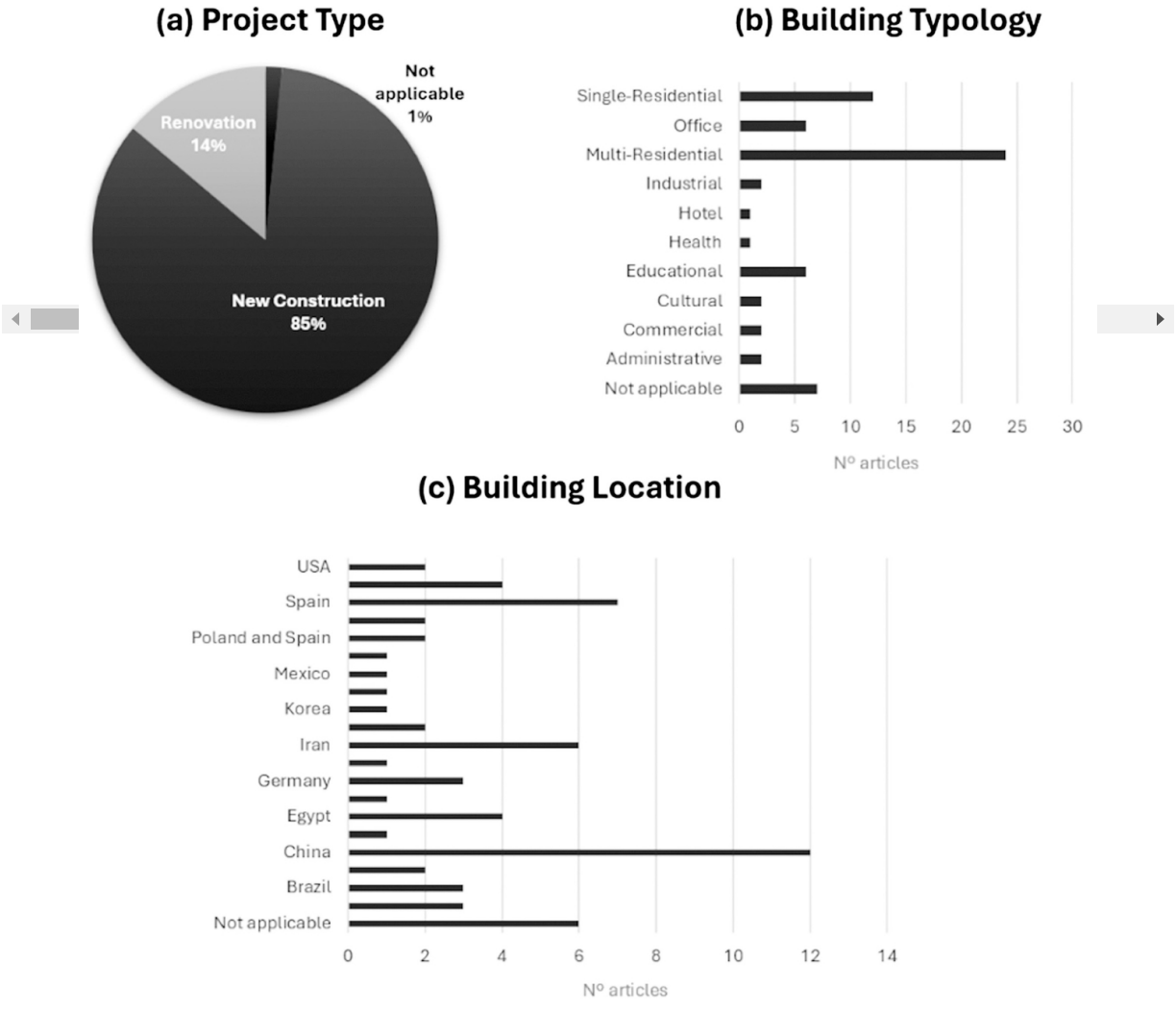


Fig. 6 Charts with the 65 publications categorised by Project Type, Building Typology, and Building Location.

The results indicated that buildings assessed in the articles were distributed across different countries and regions, with 18% located in mainland China.

3.5 Decision Support

Decisions made during a project significantly impact a building's performance over its entire lifespan. While project goals may conflict in the short and medium term, they create complex challenges. Optimisation entails identifying a function's highest or lowest value while adhering to specified constraints by adjusting multiple variables. In building design, multi-objective optimisation is often employed to tackle conflicting objectives that impede the simultaneous optimisation of all goals (Hassan et al., 2022). Various multi-objective optimisation methods, such as evolutionary algorithms, particle swarm optimisation, and the Non-Dominated Sorting Genetic Algorithm (NSGA), are applicable in this context (Hassan et al., 2024). For example, Genetic algorithms are used for analysing the trade-offs between economic and environmental factors (Martínez-Rocamora et al., 2021; Mowafy et al., 2023) refurbishment and renovation optimisation (Motalebi et al., 2022; Sharif and Hammad, 2019), for the tradeoff between embodied and operational energy (Abbasi and Noorzai, 2021), and building envelope optimisation (Atashbar and Noorzai, 2023; Tushar, Zhang, et al., 2022), for predicting the

environmental impact of different building typologies (Martínez-Rocamora et al., 2021).

Multi-Criteria Decision Analysis (MCDA) is another decision-support method. Various multi-criteria methods have been developed and applied in construction design. For example, Domingos and Rato (2019) used the MACBETH tool to find the best-fit construction materials for extreme climate scenarios, while Stellacci et al. (2024) used parametric modelling tools and multi-criteria decision analysis to find the best retrofit scenario considering energy consumption and architectural configuration. Taher et al. (2023) developed a decision support framework using the analytical hierarchy process (AHP) to choose the appropriate design alternative for sustainable buildings considering cost, time, aesthetics, availability of material and energy efficiency. Abdelaal et al. (2023) aid in ranking and selecting the type of concrete based on sustainability criteria including CO2 emissions, embodied energy, and cost using the AHP method. Filho et al. (2022) used the Fuzzy AHP to find the best design option considering environmental and socio-political criteria.

Moreover, sensitivity analysis, regression techniques, and other probabilistic methods are used to manage uncertainties through sampling and have proven particularly effective in early LCA studies (Hassan et al., 2022). These methods allow users to explore various alternatives by iteratively evaluating design variables. Sensitivity analysis has been employed in early LCA studies to help reduce the

embodied environmental impacts of building component materials and dimensioning choices (Basbagill et al., 2013; Gao et al., 2024; Heydari and Heravi, 2023; Tushar et al., 2021b) and to identify the influential factors in building LCA (Zhou, Tam, et al., 2023b) and analyse the importance of independent variables.

Despite the benefits for design-making of using the aforementioned methods, only 15% of the studies utilised the target optimisation methods, 7% employed MCDA, and 13% incorporated sensitivity analysis.

Conclusion

This study examined 65 articles on BIM-based LCA published between 2013 and March 2024. A systematic review following Prisma Guidelines was employed to answer the research question: What are the limitations, trends, and future developments of BIM-based LCA for building design?

The BIM-based LCA topic has received considerable attention during the last five years. The five hottest topics in the knowledge area have been identified as LCA, BIM, carbon emissions, global warming potential, and sustainability. Chinese researchers have been the key in the development of BIM and LCA in the construction sector, making significant contributions and serving as important players in the collaboration network.

Autodesk Revit and Graphisoft ArchiCAD are the most commonly used BIM software. Most studies do not specify the models LoD, though some identify LoD 300 as suitable

for accurate LCC and LCA calculations, while others perform simplified LCA studies with LoD 200 BIM models.

Sixty per cent of the references studied are third-party LCA tools, 23% are add-ons to BIM software, mostly Revit, and 9% where environmental information is parameterised in BIM objects. Concerning data exchange, 40% of the tools use a conventional method. This procedure is inefficient because any changes require restarting the process from the beginning, making it prone to errors and time-consuming. Additionally, 89% of the proposed methods carry out the correspondence between environmental data and the BoQ manually.

Most of the references studied performed an LCA on new-build projects, and only 35% applied a decision support method such as multi-objective optimisation, MCDA, or sensitivity analysis.

Although we have identified many different approaches to integrating BIM and LCA, this process needs further development. Our findings reveal that the major literature gaps are:

1. BIM-based LCA still requires many manual processes, such as editing the BoQ and mapping BIM objects or materials to environmental data. Both processes can be automated. The first can be addressed by adopting standardised modelling and information management strategies and using static or dynamic data exchange tools. The second can be automated by adopting a universal nomenclature, such as construction

classification systems, to establish an automatic link between BIM objects and LCA databases, enabling the application of algorithms like Natural Language Processing

2. There is a notable lack of tools that enable continuous and accurate monitoring of environmental impacts throughout all project phases. The available tools are typically adapted for either highly detailed design or early design. Future tools should align LCA databases with design phases to improve accuracy and reliability, as suggested by Cavalliere et al. (2019) and Parece, Costa, et al. (2024)
3. There is a notable lack of studies on how circular economy strategies, such as DfD and waste management, and DfA, influence the LCA results in building projects. DfD and waste management influence end-of-life scenarios, and DfA the use stage. There is a need to investigate how these stratagies are quantitatively reflected in the carbon emissions throughout the building’s life cycle.
4. There is a notable lack of methodologies adapted for renovation or refurbishment projects. These BIM models usually have different attributes, including unique modelling techniques, differentiation between existing and new structures and rehabilitation procedures, and most of the available LCA tools do not allow for interoperability and workflow automation in these cases.

5. It is evident that there remains a dearth of research on decision support methods applied to LCA in building projects, considering various indicators that frequently conflict, such as cost, operational carbon, and embodied carbon. These decision support methods can include multi-objective optimisation or MCDA.

Acknowledgement

This research was supported by the doctoral Grant PRT/BD/154261/2022, financed by the Portuguese Foundation for Science and Technology (FCT), and with funds under the MIT Portugal Program, and partially founded by ISTAR projects: UIDB/04466/2020 and UIDP/04466/2020.

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