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Building life cycle assessment and digital technologies: A bibliometric and systematic literature review and recent advances on their integration to boost the decarbonization of the construction sector

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ABSTRACT

There is growing concern about reaching the European Union Zero-Emission Building (ZEB) set by the latest recast of Energy Performance Buildings Directive. In this context, Building Life Cycle Assessment (BLCA) is one of the established methods to reach the target, especially when integrated with Building Digital Technologies (BDTs). The study aims to identify current integration strategies between BLCA and BDTs, explore barriers and opportunities, and provide insights to enhance the digitalization of LCA in the construction sector. As a result of the literature search, the main technologies involved in BLCA–BDT integration have been identified, with Building Information Modelling (BIM) dominating the field with 703 publications, followed by Artificial Intelligence (AI) with 215 and Digital Twin (DT) with 147. Following the PRISMA guidelines, the study presents a Systematic Literature Review (SLR) on the topic, based on 96 articles published over the last decade. The quantitative analysis aims to classify and evaluate the most frequent BLCA-DTs integration types, while the qualitative analysis allows an in-depth critical review based on the identification of Strengths, Weaknesses, Opportunities, and Threats (SWOT), to better understand the current state of research and its potential to support the transition toward ZEBs. The discussion of those analyses led to the development of strategic guidelines clustered with best practices to support stakeholders in leveraging BLCA-BDTs integrations. In conclusion, the study highlights the importance of early-stage integration, shared data models, and interdisciplinary skills to fully exploit the potential of BDTs in achieving ZEBs target.

1. Introduction

The construction sector represents the largest energy consumer and greenhouse gas (GHG) emitter in the European Union (EU), accounting for approximately 40 % of the total energy consumption and 36 % of its energy-related GHG emissions, while 75 % of EU buildings are energy-inefficient [1]. Reducing emissions from this sector is therefore essential to achieving the EU's objective to become the first carbon–neutral continent by 2050, as set out in the European Green Deal in 2019 [2]. The EU has introduced a legislative framework comprising the revised Energy Performance of Buildings Directive (EPBD) (EU/2024/1275) [1] and the revised Energy Efficiency Directive (EED) (EU/2023/1791) [3] to address this challenge and to promote policies among Member States that facilitate the transition towards an energy-efficient and decarbonized building stock by 2050. The EPBD 1275/2024 introduces the definition of Zero Emission Building (ZEB) as a building with very high energy performance and no on-site carbon emissions from fossil fuels and set the target of ZEB from 2028 for all new public buildings, and from 2030 for all other new buildings [1].

To achieve a zero-emission building stock, it's essential to

Abbreviations: BDTs, Building Digital Technologies; BIM, Building Information Modelling; BLCA, Building Life Cycle Assessment; BoQ, Bill of Quantities; DT, Digital Twin; EED, Energy Efficiency Directive; EPBD, Energy Performance of Buildings Directive; EU, European Union; GHG, Greenhouse Gas; IFC, Industry Foundation Classes; IoT, Internet of Things; LCA, Life Cycle Assessment; LCI, Life Cycle Inventory; LCSA, Life Cycle Sustainability Assessment; LOD, Level Of Development; ML, Machine Learning; PRISMA, Preferred Reporting Items for Systematic Reviews and Meta-Analyses; RQ, Research Question; SLR, Systematic Literature Review; SWOT, Strengths, Weaknesses, Opportunities, and Threats; ZEB, Zero-Emission Building.

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understand how the construction sector contributes to carbon emissions and when these emissions occur [4]. Building-related emissions can be grouped into two main types: operational and embodied emissions. Operational emissions are related to the energy used for electricity, heating and cooling systems of buildings. These can be reduced over time by shifting to renewable or clean energy sources [5]. On the other hand, embodied emissions are connected to the materials used throughout a building's life, from production and transport to installation and disposal. Unlike operational emissions, embodied carbon cannot be reduced once the construction process is finished. Hence, it's crucial to choose low-carbon material early in the design process to minimize the building's overall carbon emissions [6].

Besides knowing the types of emissions of a building, to reach the zero-emission building goal, it's crucial to implement and use assessment methods and frameworks to holistically evaluate the environmental impacts of buildings, by addressing different performance aspects, including energy efficiency, GHG emissions and circularity level [7,8]. In this context, Building Life Cycle Assessment (BLCA) is one of the most common methods to evaluate the environmental aspects of the construction sector, and to identify the possible solutions to reduce buildings' impacts throughout their life cycle [9–11]. By taking into account factors such as energy use, GHG emissions, and resource consumption, BLCA provides a complete assessment of a building's environmental footprint. It helps identify the "hot spots" of a building, e.g., the most impactful phases, processes, systems and materials, and allows more informed decisions about design, construction, use, and end-of-life stages, helping to reduce GHG emissions [12,13].

However, BLCA application features several challenges, such as difficulties in accessing reliable and detailed data to ensure transparency and traceability, the technical complexity of the impact assessment process, the risk of misinterpreting the results, and the considerable time required to carry out the LCA analysis [14–17].

In this context, the application of Building Digital Technologies (BDTs) is becoming an effective solution to optimize BLCA and enhance ZEBs [18,19]. Innovations such as Building Information Modelling (BIM), Digital Twin (DT) and Artificial Intelligence (AI) enable real-time modelling, better data integration, and predictive analysis, revolutionizing the way buildings are designed, built and used [20]. The integration of BDTs with BLCA can optimize how data is collected, organized, and managed, making the assessment process more transparent and traceable [21–23]. These DTs also facilitate data sharing and ensure secure information exchange throughout the life cycle assessment [24–27].

Although both LCA and digital technologies have become hot topics in the construction sector, with an exponentially growing body of research on each of them individually, their effective integration is still underexplored [28]. Recent studies highlight the potential of AI and Machine Learning (ML) techniques to enhance carbon emission calculations, predict environmental impacts, and accelerate low-carbon material discovery [29,30]. Similarly, BIM and DT models have been proposed to automate life cycle inventory processes and improve the accuracy of LCA assessments [31–33]. Despite these advancements, current applications remain fragmented, with limited methodological standardization and uncommon validation in real building projects [34,35]. While designers, contractors, policymakers, and technology developers often use LCA and digital solutions in parallel, there is still no clear and standardized approach to effectively combine them. This fragmentation limits the potential of such integration to systematically support the achievement of ZEB.

This research gap underlines the novelty of the present study, which aims to identify how BLCA and BDTs integration can enhance the transition towards a ZEB stock through a bibliometric analysis and Systematic Literature Review (SLR). Following the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) statement [36], a total of 96 peer-reviewed articles published between 2016 and 2025 have been identified and then analyzed with a quantitative and qualitative methodology. The quantitative one aimed at identifying and studying which BDTs are most frequently integrated with BLCA in the literature, while the qualitative one, based on a SWOT analysis, allowed to better understand benefits, limitations, opportunities, and challenges of those integrations.

This work aims to consolidate a grounded knowledge base that supports different target groups, from academic researchers to construction sector stakeholders, in conducting high-quality and user-friendly digitalized building sustainability assessment. By offering a critical overview of the state of the art and highlighting research gaps, the paper provides a foundation for future investigations and developments in BLCA digitalization. It also aims to support practitioners, policymakers, and software developers in identifying priorities, aligning standards, and co-developing interoperable and efficient digital sustainability frameworks for the construction sector.

Three Research Questions (RQs) have been identified to guide this investigation: RQ1 – "Which are the most common BLCA-BDTs integrations in the construction sector?"; RQ2 – "How can these integrations boost the decarbonization process of the construction sector?"; RQ3 – "How can different target groups use these integrations to boost the decarbonization process of the construction sector?". Following the contextualization and motivation of the study presented in the introduction, section 2 outlines the methodology adopted for the SLR, including the research strategy, the selection criteria, and the data analysis procedures. Section 3 presents the bibliometric analysis, followed by section 4, which presents the critical review of the selected literature, structured into a dual analysis: quantitative analysis and qualitative. In section 5 the results are critically discussed through a SWOT analysis, and a series of guidelines are developed. Finally, section 6 provides the conclusions of the work by summarizing the main insights and guidelines on the topic studied.

2. Methodology

Referring to the research framework and the RQs presented in section 1, the overall methodology is presented in this section and summarized in Fig. 1, with a specific focus on the approach followed for the SLR.

The overall structure of the paper has been designed to ensure consistency, transparency, and reproducibility, aligning with consolidated approaches used in recent systematic literature reviews in the construction and sustainability domains.

Following the contextualization and the definition of the RQs presented in the introduction, Section 2 illustrates the methodological workflow adopted for the SLR. The identification of the literature on the topic for the SLR followed the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines to guarantee methodological rigor and quality, using three thematic domains in two-step research: life cycle assessment, digital technologies, and the construction sector; and combined through Boolean syntax to formulate the final queries.

The final list of studies has been analyzed through three different perspectives: a bibliometric analysis in Section 3, followed by a dual quantitative and qualitative analysis of the overall results. The quantitative analysis in section 4 allowed the classification of the most common BLCA–BDT integration typologies and provided an overview of their temporal and geographical distribution. The qualitative analysis in section 5, instead, supported by a SWOT framework offered an in-depth evaluation of the strengths, weaknesses, opportunities, and threats associated with such integrations, highlighting both the scientific advances and the persistent barriers that still hinder their widespread application.

The results of the analyses were subsequently synthesized into a set of strategic guidelines and practical recommendations. These guidelines address four main domains: design processes, data standards, digital infrastructures, and interdisciplinary training; and are complemented by

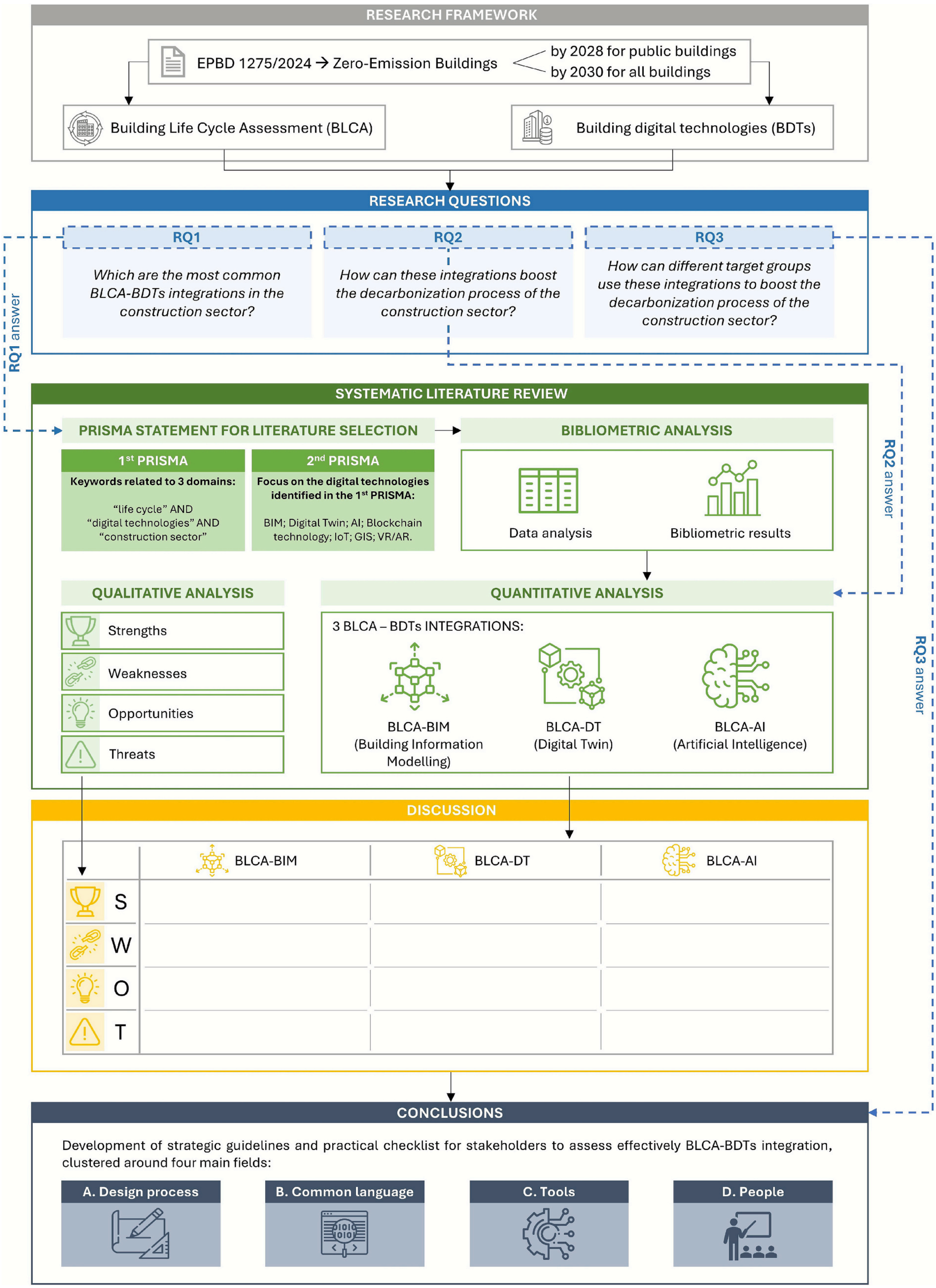

Fig. 1. Graphical summary of the overall methodological framework of the study.

a practical checklist to support their adoption by researchers, practitioners, and policymakers. In this way, the methodological workflow ensures a comprehensive and critical overview of the literature, enabling the formulation of evidence-based insights that can effectively guide the digitalization of life cycle assessment in the construction sector.

2.1. PRISMA statement

This study adopted the PRISMA [36] guidelines to conduct the SLR to investigate which BDTs are currently supporting the implementation and automation of BLCA, as well as how their integration can enhance the transition towards ZEBs. The SLR aims to answer the RQs presented in the previous section. The use of the PRISMA approach ensures methodological transparency, reproducibility, and consistency, aligning with consolidated practices in literature review. Moreover, to include all the significant articles related to the research topic, a two-step approach has been applied.

– 1st PRISMA: to identify the overall literature addressing BLCA–BDTs integration and to determine which technologies are most frequently investigated.
– 2nd PRISMA: to focus on the integration of the individual technologies identified in the first search with BLCA, enhancing the final sample by including studies that may not explicitly use the generic terms adopted in the first query.

Three thematic domains have been combined in the search query for the 1st PRISMA: “life cycle”, “digital technologies”, and “construction sector”. The first two domains, and their most common scientific declinations, have been used to identify studies addressing both fields, and then filtered during the PRISMA phases to keep only those explicitly focused on their integration. The third domain, “construction sector”, filters the results to the sector of the research. Table 1 presents the list of the final terms chosen for the literature study, selected after an extensive iterative testing process, to identify the most relevant and accurate results. The academic databases Scopus and Web of Science have been selected for their extensive interdisciplinary coverage of literature relevant to the built environment. During the initial research process, only peer-reviewed journal articles, conference papers and relevant book chapters have been considered to ensure the quality and relevance of the results.

The initial quest identified 1345 potentially relevant documents: 858 from Scopus and 487 from Web of Science. After removing the duplicates and the articles marked as ineligible by automation tools, 1013 research documents have been identified for the selection process, which comprises the following sequential phases.

– Screening phase: the articles have been filtered based on language (English) and publication year (2016–2025). These criteria narrowed down the number of publications to 832 papers.
– Eligibility phase: titles, abstracts and conclusions of the articles have been reviewed to identify studies that addressed LCA and BDTs topics within the context of the construction sector. Articles focusing exclusively on other specific sectors, such as industrial manufacturing, energy production, or unrelated digital applications, were excluded, and 314 papers remained for the last phase.
– Inclusion phase: full-text reading of the eligible studies has been conducted to verify their relevance to the research topic. Only studies presenting a clear theoretical or practical analysis of the LCA and BDTs integration have been considered. After assessing eligible studies based on the inclusion criteria, 85 papers have been selected for the SLR.

Table 1
List of the search terms used in the final query.

Thematic domain	Search terms
Life CycleAssessment	TITLE-ABSTRACT-KEYWORD (“life cycle assessment” OR “life cycle analysis” OR “lifecycle” OR “life-cycle” OR “LCA” OR “environmental impact*” OR “environmental assessment*”)
Digital Technologies	TITLE-ABSTRACT-KEYWORD (“digital technolog*” OR “digitalization” OR “digitalisation”)
Construction sector	TITLE-ABSTRACT-KEYWORD (“construction sector” OR “construction industr*” OR “construction product*” OR “building*” OR “built environment” OR “building product*” OR “building industr*”)

The full-text review allowed the identification of the digital technologies studied in literature in relation to BLCA integration in the construction sector: Building Information Modelling (BIM), Digital Twin, Artificial Intelligence (AI), Blockchain, Internet of Things (IoT), Geographic Information Systems (GIS), and Virtual/Augmented Reality (VR/AR). At the light of these results, the 2nd PRISMA search has been performed to deeply investigate digital technologies identified in the 1st PRISMA and also to improve the robustness of the review and reduce the risk of overlooking relevant contributions. For these reasons the query structure has been updated by replacing the generic terms related to “digital technologies” with specific keywords referring to the eight technologies identified. Fig. 2 illustrates the revised query structure. The same phases and exclusion criteria applied in the 1st PRISMA guided the 2nd one. This additional investigation led to the inclusion of 11 further articles, resulting in a final dataset of 96 manuscripts.

Table 2 details the workflow of the 2nd PRISMA search and the overall results in terms of included and excluded manuscripts. The final selection provides the basis for the bibliometric analysis in Section 3, followed by a dual quantitative and qualitative analysis of the overall results, respectively presented in section 4 and section 5.

3. Bibliometric analysis

A preliminary bibliometric analysis has been conducted on the 96 selected manuscripts to explore the evolution, distribution, and thematic orientation of scientific literature related to BLCA and Digital Technologies integration within the construction sector, focusing on the temporal frame of the last ten years and considering different geographical contexts.

The evolution of publication trends in the integration of BLCA and BDTs has been assessed through the application of the Mann–Kendall test, a non-parametric statistical method widely used to detect monotonic trends in time-series data, particularly when the dataset may present irregularities or does not follow a normal distribution. In this study, the MK test has been employed to examine the temporal distribution of publications on the integration of BLCA and BDTs, to determine whether the number of studies has been increasing, decreasing, or remaining stable over time.

The test evaluates the presence of a statistically significant trend by computing two main parameters: the standardized test statistic (z-value), the probability value (p-value) and Kendall’s Tau (τ-value). A positive z-value indicates an upward trend, while a negative z-value suggests a downward trend. The p-value, in turn, measures the strength of the evidence against the null hypothesis of no trend. When the p-value falls below a predefined significance threshold (typically 0.05), the null hypothesis is rejected, and the trend is considered significant. Finally, Kendall’s Tau provides a correlation coefficient ranging from -1 to $+1$ that quantifies the degree of monotonic association between time and the variable of interest, with values closer to ± 1 indicating stronger trends.

This approach allows a robust understanding of the dynamics of the research field, as it provides evidence on whether academic attention towards BLCA–BDTs integration is gaining momentum, stagnating, or declining. Table 3 summarizes the results of the Mann–Kendall test, including the direction of the trend, z-value, p-value, τ-value and the

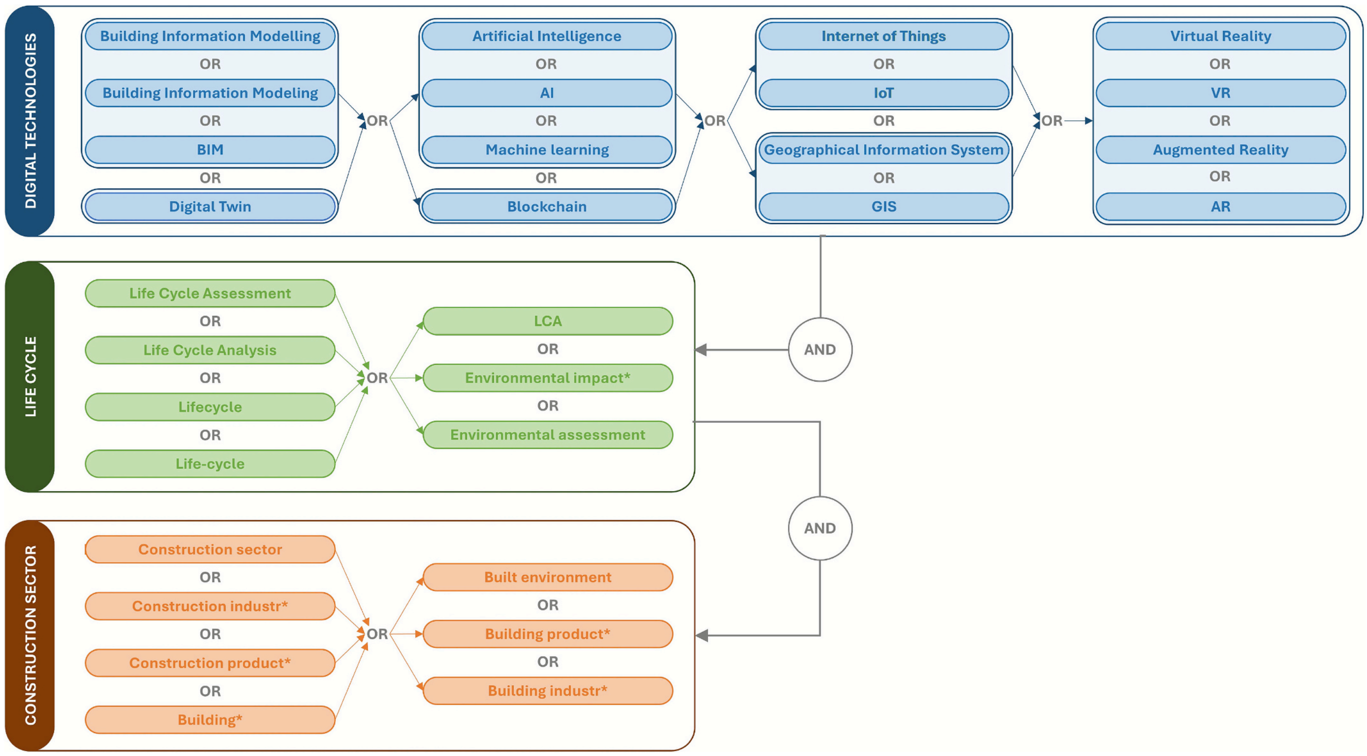

Fig. 2. Core domains and keyword nesting for the systematic review on BLCA-BDTs integration.

Table 2
Results for each step of the 2nd PRISMA statement.

PRISMA statement	Number of documents	
Identification	Records identified from: Scopus = 1553 Web of Science = 546	Records removed before screening: Duplicate records removed = 457 Record marked as ineligible by automation tools = 106 Duplicate records from 1st PRISMA removed = 1332
Screening	Record screened = 204	Record excluded = 34
Eligibility	Records assessed for eligibility = 170	Record excluded = 106
Inclusion	Records assessed for inclusion = 64	Record excluded = 53
Final selection	Records selected for the review: from the inclusion phase = 11	

Table 3
Results of the Mann–Kendall test applied to the identified publication dataset on BLCA–BDTs integration.

Mann-Kendall parameters	Results
Trend	Increasing
z-value	3.5777
p-value	3.47×10^{-4}
Significance	Significant
τ-value	0.91

level of statistical significance, offering a clear picture of the trajectory of scientific production on this topic.

The results of the Mann–Kendall test indicate a statistically significant and upward trend in the number of publications addressing the topic of this study. The z-value of 3.5777, well above the critical threshold of $\pm$ 1.96 for a 95 % confidence level, indicates a consistent monotonic increase over the considered time period. The associated p-value (3.47×10^{-4}) falls far below the conventional 0.05 threshold, supporting the rejection of the null hypothesis of no trend. Furthermore, Kendall's Tau ($\tau = 0.91$) reveals a very high positive correlation between time and publication frequency, suggesting that the increase is not only statistically significant but also of considerable scale. The high τ-value confirms that the observed increase is systematic and reflects a consolidated growth in research attention to this topic.

Following the Mann–Kendall test, a regression-based analysis has been conducted to provide insights into the possible evolution of research activity in the coming years. Fig. 3 illustrates the trend of scientific publications from 2016 to 2024, together with the projected trajectories up to 2030. The increase observed over the past decade, approximately 1033 % (from only 3 publications in 2016 to 31 in 2024), highlights the growing relevance of BLCA–BDTs integration. This rise reflects not only the scientific community's interest in sustainability but also the influence of standards, regulations, and directives introduced worldwide, and particularly in Europe, to support decarbonization targets and digitalization strategies. For the period 2025–2030, two regression models have been applied to capture both the short-term acceleration of publications and the long-term trajectory of the research field: a linear regression considering only the most recent trend (2020–2024) and a polynomial regression considering the entire dataset (2016–2024).

The comparison between the two models highlights different possible trajectories. The linear trend reflects a conservative estimate that assumes continuity of the recent growth rate, while the polynomial regression captures the accelerated increase observed since 2016, indicating the potential for exponential expansion of the research domain. Although projections beyond short time horizons should be interpreted cautiously, both models consistently point towards a substantial increase in scientific output, reinforcing the results of the Mann–Kendall test. These findings underline the consolidation of BLCA–BDTs integration as a rapidly emerging research area, with growing relevance in the scientific community and implications in policies and practices in the construction sector.

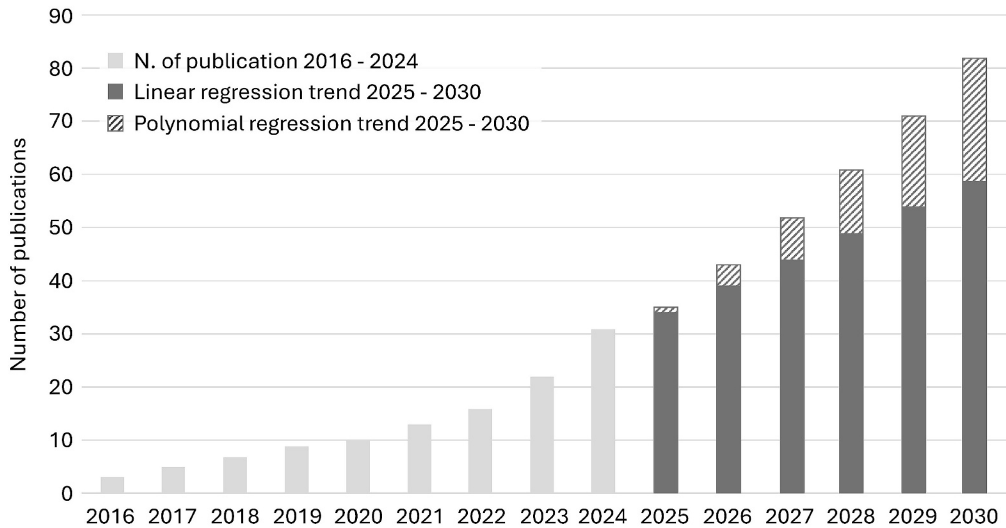

Fig. 3. Publication trend and forecast per year (x-axis) and number of publications (y-axis), referring to the PRISMA results.

The analysis of document types (Fig. 4) reveals that journal articles are the most typology analyzed, with 71 documents (74 %). Conference proceedings account for only 8 publications (8 %), despite the importance of international scientific events as early dissemination channels for emerging research topics. This distribution reflects the current research maturity level of the topic: while journal articles dominate and validate methodological developments, the presence of conference papers suggests that the field is still under active exploration, with ongoing experimentation and collaboration among research institutions, practitioners, and standardization bodies.

Although review articles are fewer than research articles (15 documents, 15.6 %), they play a strategic role in consolidating knowledge, particularly in a domain where methodological integration between BLCA and BDTs remains fragmented. The limited number of book chapters (2, 2.2 %) confirms that the topic is still primarily addressed through academic journals rather than long-format or applied professional contributions with grounded statements useful for the practical application to the design value chain of constructions.

Considering the distribution of publications across academic journals, as graphically represented in Fig. 4, it emerged that the discussion on BLCA and BDTs integration is led by scientific journals like Sustainability, Journal of Building Engineering, and the International Journal of Life Cycle Assessment, which collectively account for 36 % of the literature and they covers all aspects of science and technology concerned with the whole life cycle of the built environment; from the design phase through to construction, operation, performance, maintenance and its deterioration, being interdisciplinary journals. Moreover, the publications' relevance highlights the field's interdisciplinary nature, connecting engineering, environmental science, and information technology. Additionally, the presence of specialized journals, such as the Journal of Cleaner Production and Energy and Buildings, highlights the growing interest in energy efficiency and low-carbon building design within the context of digital transformation.

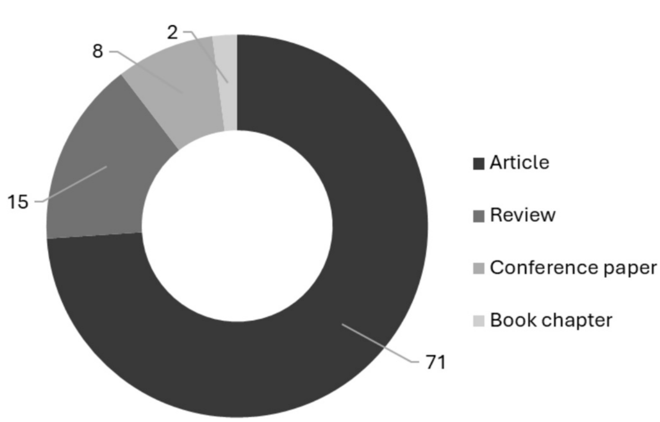

Fig. 4. Breakdown of the number of global scientific outputs on BLCA-BDT integration in the construction sector per document type, according to the Scopus and Web of Science databases.

Looking at the geographical distribution and correlating this aspect with the journal's types, Fig. 5 reveals some interesting differences between the world regions. The European Union has a predominant role in research related to the topic, with a high share of papers belonging to different journal's types, up to 86 % in The International Journal of Life Cycle Assessment and consistently above 60 % in Sustainability and Energy & Buildings. This indicates a strong European leadership in driving the LCA–digitalization agenda, likely reflecting the EU's ambitious climate targets and policy frameworks. In contrast, contributions from regions such as the USA–Canada, South America, the Middle East, India, and Africa remain marginal across most journals, with only scattered contributions peaking slightly in Environmental Impact Assessment Review and Built Environment Project and Asset Management for USA-Canada with a share of 33 %, Journal of Building Engineering for South America Countries (25 % of share), Buildings for Middle East region (22 %) and Construction Innovation for both Africa and India (with a 33 % of share). Asia (especially China) appears more prominently in some journals, Sustainability, Journal of Cleaner Production, Building and Environment and Environmental Impact Assessment Review. Oceania shows only modest representation, mainly in the Journal of Cleaner Production and Buildings.

The keyword frequency and co-occurrence analysis (Fig. 6) highlights the thematic focus of the literature. The five most-used keywords are: (i) Building Information Modelling (BIM – used 71 times); (ii) Life Cycle Assessment (LCA – 67 times); (iii) sustainability (14 times); (iv) carbon emissions (7 times); and (v) Construction Industry (6 times). The graph in Fig. 5 considers only keywords that have been used in at least 2 publications. The coexistence of high-level conceptual terms and practical application-related keywords suggests a dual evolution of the field: one toward operational integration in design practice, and the other toward infrastructure-level standardization and data automation.

Finally, Fig. 7 presents the evolution of BDTs terms from 2000 to 2025 based on the number of occurrences the most frequently studied integration typologies between BLCA and BDTs within the reviewed literature. The majority of studies focus on the use of Building Information Modeling (BIM) as a digital platform to support BLCA

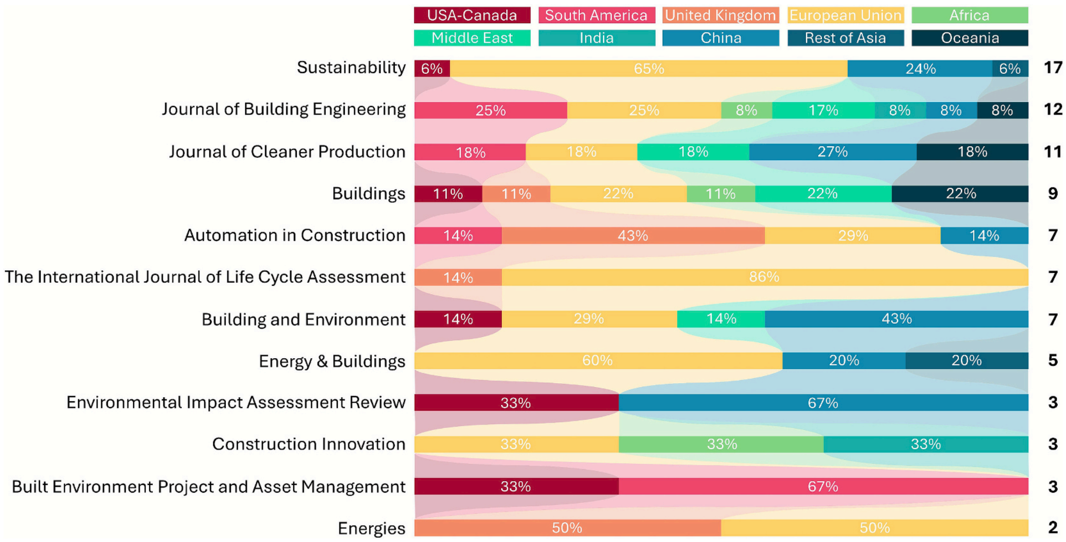

Fig. 5. Bibliometric analysis of the selected documents comparing journal's types and geographical distribution.

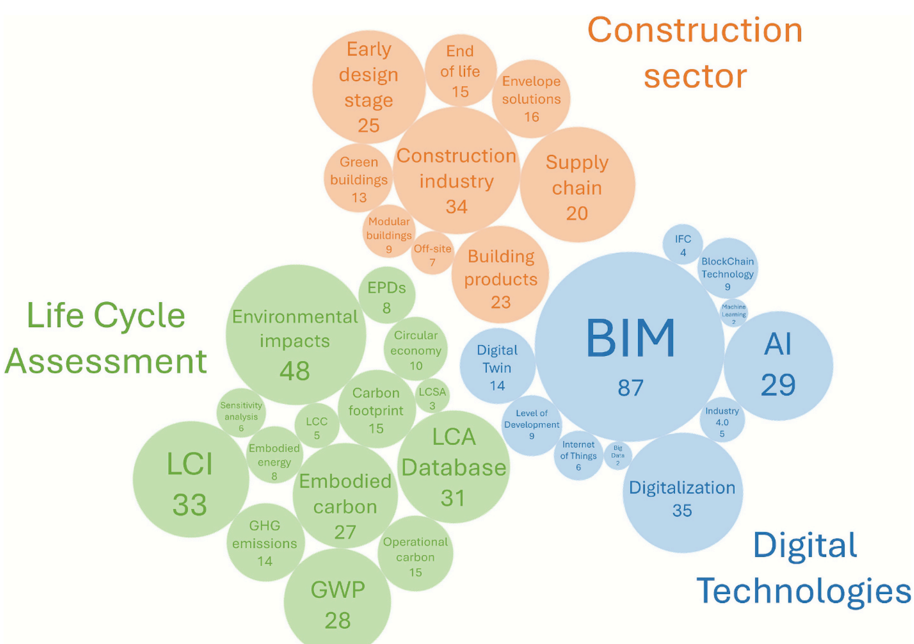

Fig. 6. Bubble graphical representation of the most common keywords used in the articles included in the SLR and core topics clusterization.

implementation, often through semi-automated or fully integrated workflows. BIM is frequently coupled with other instruments or methodologies such as Life Cycle Inventory (LCI), parametric modeling, and energy simulation software, highlighting its central role in facilitating data exchange and improving the transparency and repeatability of LCA processes.

Another relevant cluster of studies investigates the combination of BLCA with Digital Twin (DT), particularly in urban-scale assessments and renovation scenarios. Those integrations facilitate spatially explicit environmental analyses and multi-scenario comparisons. Emerging approaches include the adoption of Artificial Intelligence (AI) to enable real-time data collection, traceability, and enhanced decision-making in LCA applications.

4. Results

The bibliometric analysis highlights how Building Information Modelling (BIM), Digital Twins (DT), and Artificial Intelligence (AI) are the most frequently studied types of BDTs concerning their integration with LCA in the construction sector. This section explores these three BLCA-BDTs integrations in detail through a two-step literature review approach: a quantitative analysis (section 4.1) followed by a qualitative one (section 4.2). The quantitative analysis aims to understand how the integrations between BLCA and the selected BDTs are being studied and applied in the existing literature. The qualitative analysis, on the other hand, uses a SWOT framework to investigate the benefits and limitations of these integrations.

4.1. Quantitative analysis

This section presents the results of the quantitative analysis conducted on the selected literature to map the current landscape of BDTs investigated regarding their integration with BLCA. Three main DTs emerged as the most frequently explored in literature in connection with

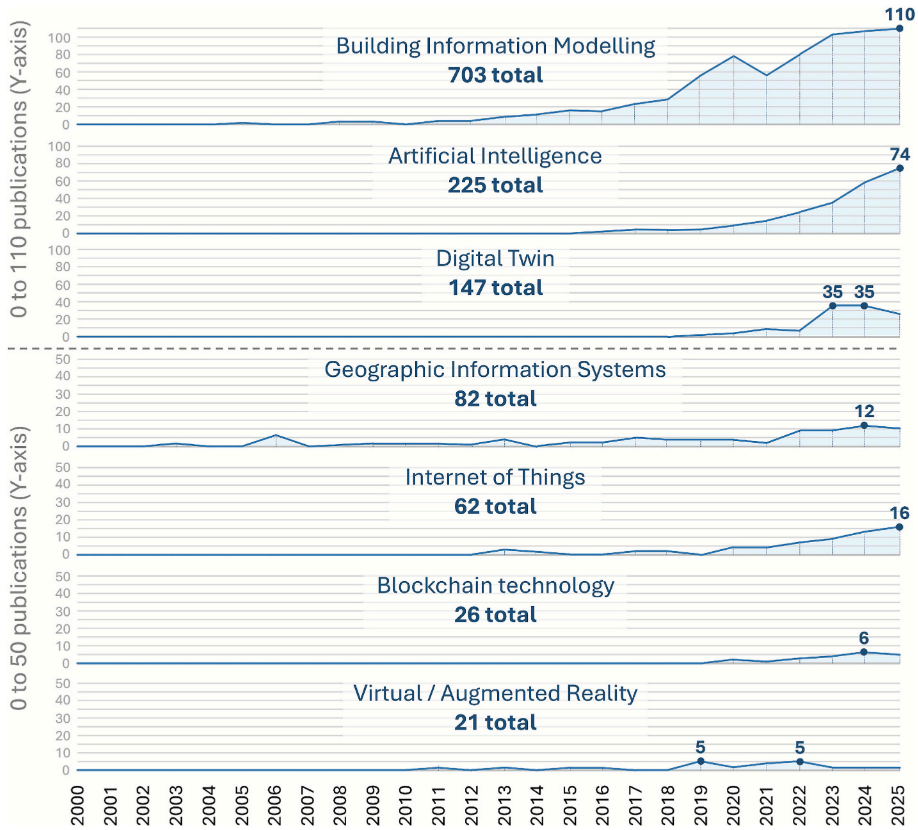

Fig. 7. Graphical representation of the most occurring BLCA-BDTs integration typologies identified by SLR.

Building LCA: BIM, DT, AI. The following subsections provide a detailed overview of how these technologies are integrated with LCA, along with the classification frameworks proposed in the literature. The final subsection provides a concise quantitative analysis of the integrations between BLCA and other digital technologies identified in the literature, specifically the Internet of Things (IoT), Geographic Information Systems (GIS), Blockchain technology, and Virtual/Augmented Reality (VR/AR). Although these integrations are less widespread than those discussed in the other subsections, examining them offers a more comprehensive overview of the digital approaches supporting Building Life Cycle Assessment.

4.1.1. BLCA-BIM integration

Building Information Modelling (BIM) is a digital language used in the construction sector as a workspace for the building model generation, storage, and exchange of data throughout the project lifecycle, promoting interoperability and data reuse across stakeholders [37,38]. In the early design and pre-construction phases, BIM is widely adopted as a collaborative platform that integrates inputs from diverse actors within a shared digital workspace [39]. Beyond its role in design coordination, BIM's capacity to centralize and organize information makes it particularly valuable for supporting sustainability-oriented decisions [40,41]. In this context, integrating BIM language with the BLCA methodology is becoming a growing research area in literature with the potentiality to provide a valuable resource for improving the sustainability evaluation process, enhancing data acquisition and minimizing manual input requirements in the construction sector [42,43]. This synergy improves computational efficiency, allowing faster and more holistic sustainability assessments [39,44].

As integration of BIM with LCA gains traction in the literature, various classifications have been studied in recent years [45,46], focusing on the connection between BIM and Building LCA. However, there is still no agreement on which integration approach offers the best balance between accuracy, efficiency, and practical applicability in different contexts.

One of the earliest attempts to classify BLCA-BIM integration was presented by Antón and Díaz [47], who identified two different approaches. The first one is based on extracting information from the BIM model using standardized data interchange protocols such as Industry Foundation Classes (IFC). This allows real-time assessment of design alternatives and helps to reduce the need for manual data entry, while the second approach works with the inclusion of environmental attributes directly within BIM objects, so that each element has its environmental profile throughout the design process. This requires dynamic data updating in parallel with project development and it poses specific challenges in integrating information related to transport, maintenance, and other life cycle stages.

This initial classification was further improved by Soust-Verdaguer et al. [48], who proposed a three-level framework. At the first level, BIM is used as a support tool during the LCI phase in order to help the quantification of materials and components of a building. The second level focuses on the introduction of environmental and energy-related parameters into BIM objects, allowing the connection of inventory data and preliminary impact assessments within the design environment. The third level refers to the automation of the BIM-LCA workflow, achieved by establishing connections between BIM platforms and LCA software through dedicated plug-ins or interoperable databases, thus supporting continuous information flow and reducing the margin for error in data translation [49].

In more recent studies, the most comprehensive classification was proposed by Wastiels and Decuypere [50] which divided the BIM software data exchange with LCA tools into five strategies. The first two are based on the direct export of data from BIM software, either via a Bill of Quantities (BoQ) or through the IFC format. In the third strategy, BIM data is processed using a dedicated BIM viewer before being transferred to the LCA tool. The fourth strategy is based on the implementation of

LCA-specific plug-ins directly within the BIM platform, while in the fifth one environmental data are directly integrated within BIM objects.

Furthermore, Safari and AzariJafari [51] proposed an alternative classification based on how data are collected, processed, and computed within BIM-LCA workflows. They identified three main categories: conventional, static, and dynamic approaches. In the conventional approach, BIM serves primarily as a source of quantity take-offs, which are exported into Excel spreadsheets. The extracted data is then either manually input into LCA software or used to perform simplified LCA calculations directly within the spreadsheet [52]. The static approach involves exporting BIM models into IFC format and importing them into dedicated LCA tools. In this configuration, BIM functions as both a data container and an exchange platform, enabling users to modify model parameters and update LCA results [53]. Finally, the dynamic approach is based on the creation of automated, bidirectional links between BIM models and LCA datasets. This strategy enables continuous management between design changes and environmental assessments, supporting more temporally sensitive LCA outputs [51].

Moreover, the literature proposes additional classification frameworks to describe the level of BLCA-BIM integration, focusing on the automation degree. Potrč Obrecht et al. [54] identified three integration levels based on the automation degree: (1) manual, (2) semi-automated, and (3) fully automated. Manual workflows require extensive user intervention for data extraction, formatting, and transfer between BIM and LCA tools, making them time-consuming and prone to human error. Semi-automated approaches automate part of the data exchange, typically through export functions or data mappings, but they still rely on manual operations for importing results or interpreting outputs. Fully automated methods, often implemented via plug-ins, offer a “one-click” integration in which the entire workflow, from model data extraction to impact calculation, is handled within a unified platform. However, despite their user friendliness, such tools have been criticized for their lack of transparency, as the assessment process is often encapsulated in black-box algorithms with limited user control [55,56].

The analysis of existing classification types enabled the identification of five distinct categories of BLCA–BIM integration. These categories are illustrated in Fig. 8, which also indicates the studies in which each integration type has been adopted.

The comparative analysis of existing BIM–BLCA integration approaches shows that conventional workflows, such as extracting Bills of Quantities (BoQs) from BIM software and using them as the basis for LCA modelling, generally provide the most accurate LCA results. However, these methods are also the most resource-intensive, both in terms of time and cost. Plug-in-based BIM–BLCA integration offers significantly higher computational efficiency and faster data exchange, but introduces an estimated uncertainty of approximately 6 %, as reported by Zheng 2025 [57]. IFC-based integration, which relies on openBIM principles, yields life-cycle impact assessments with acceptable levels of accuracy, with deviations of around 1 %.

Overall, these findings highlight that the selection of an appropriate BIM–BLCA integration strategy should be informed by the specific requirements of the assessment. When analysis speed is the priority, plug-in-based integration represents the most suitable option. Conversely, when result accuracy is the primary concern, BoQ-based or IFC-based workflows are more appropriate.

In the literature, several practical applications of BIM–BLCA integration have been documented across different building types and considering various life-cycle stages. Appendix A provides a detailed overview of these applications, specifying for each case the building typology, the life-cycle phases included, the adopted BIM–BLCA integration strategy, and the tools used for the analysis.

The review of these studies shows that Revit is by far the most commonly used BIM platform for LCA integration, with approximately 90 % of the identified studies relying on it. In contrast, a wider range of tools is used for the LCA component, with SimaPro, One Click LCA, and Dynamo emerging as the most frequent choices. Plug-in-based integration is the predominant approach, with eleven studies explicitly presenting the use of plug-ins to perform LCA within the BIM environment. A representative example is the study by Viscuso et al. [58], who assessed the whole-life environmental impacts of an office building

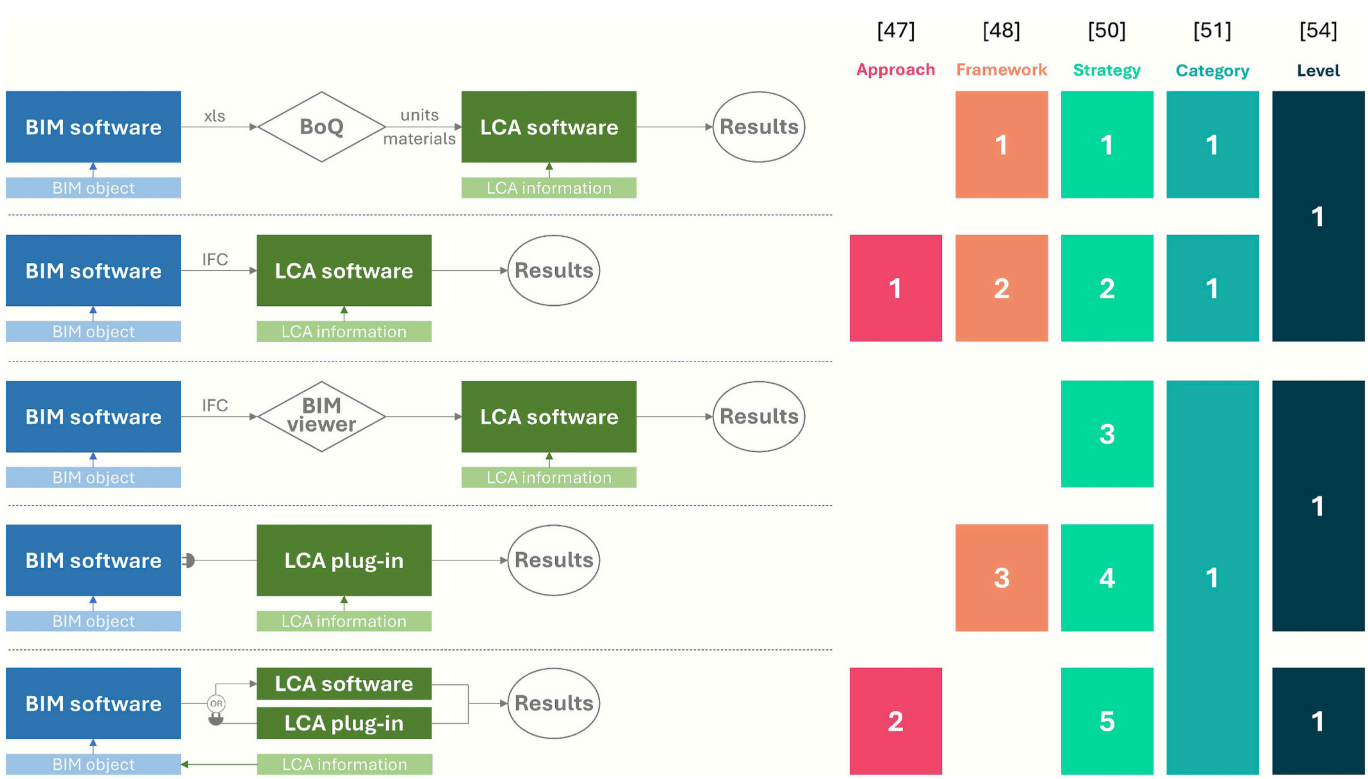

Fig. 8. Flowchart of the different types of BLCA-BIM integration according to the classification of [4748505154].

using Revit for modelling and the One Click LCA plug-in for impact calculation. This workflow enabled faster analysis times and the generation of accurate, easily manageable results within the same environment, supported by Revit's parametric information management capabilities.

Conversely, embedding life-cycle information directly into BIM objects remains a less common BLCA–BIM integration strategy, due to the substantial time required and the difficulty of obtaining reliable environmental data. An illustrative example is provided by Veselka et al. [59], who developed ENVI-MAT, a tool designed to integrate material-specific impact data into BIM objects for use within Revit. This approach allows highly detailed and material-specific environmental assessments and supports more informed decision-making regarding lower-impact design solutions, albeit at the expense of longer modelling times.

The analysis of the literature also highlights IFC approaches, which are based on OpenBIM principles, as an emerging type of BLCA-BIM integration. Numerous studies highlight how this type of integration strategy enables more effective information exchange among stakeholders involved across the entire building life cycle. OpenBIM procedures rely on non-proprietary, open data formats, with IFC being the most widely adopted standard.

For instance, Theiben et al. [60]employed OpenBIM tools to develop an integrated assessment of the environmental impacts associated with building services, such as heating, ventilation, air conditioning, and refrigeration, within a whole-building LCA framework. Their results demonstrate that OpenBIM significantly facilitates information flow between the actors involved, enabling faster and more comprehensive evaluations of life-cycle environmental impacts. Similarly, Forth et al. [61] leveraged OpenBIM-based workflows to develop a tool intended for use in the early design stages, supporting the assessment of how different material and technological choices affect environmental performance over the entire life cycle of a building. By relying on open data formats, their approach also enables non-expert stakeholders to better understand LCA outcomes and to identify lower-impact design solutions.

4.1.2. BLCA-DT integration

The Digital Twin (DT) concept is currently gaining traction in a variety of industries, including the built environment [62–65]. A DT is essentially a virtual replica of a physical asset known as a Physical Twin, with the two connected via continuous data flow, allowing for real-time analysis, monitoring, and optimization of performance parameters [66,67]. In their study, Tao and Zang [68] identified five fundamental components of the DT: the physical asset (1), the virtual representation (2), data storage systems (3), communication lines (4), and an extra service layer (5) that allows for analytical or operational functionalities.

Unlike BIM, which is generally utilized as a centralized, static repository of building data [69], DT allows for continuous, real-time interaction with the physical asset (Fig. 9). This dynamic connection enables real-time monitoring, predictive analysis, and decision support across the asset's lifecycle [70]. Building DT can vary in complexity according to the objective and type of data available, ranging from static models at the design phase to fully functioning systems during the use of one. The integration of BLCA with DT presents a significant opportunity for improving sustainability assessments in the construction sector. Traditionally, BLCA is based on static datasets and generalized assumptions, limiting its applicability for continuous performance monitoring. By integrating it within the DT infrastructure, stakeholders can transition from static evaluations based on non-updated information to dynamic, iterative sustainability assessments throughout the design, construction, operational, and demolition stages of a building's life cycle [28].

For instance, Boje et al. [66] proposed a comprehensive framework that combines BIM and DT to support Life Cycle Sustainability Assessment (LCSA), integrating environmental, economic, and social dimensions. Their approach emphasizes the dynamic nature of DT, particularly during the operational stage of buildings, where real-time sensing of parameters such as energy consumption and indoor environmental quality is integrated into the assessment workflow. The data collected through DT are used to update and refine BLCA inputs at multiple phases of the building life cycle. This creates an evolving digital representation that supports iterative sustainability evaluations through monitored and scenario-based data layers. Similarly, Figueiredo et al. [71] highlight the use of DTs to evaluate the embodied carbon of different structural solutions. Their approach relies on the continuous updating of design parameters through DT technologies, improving the reliability of environmental assessments and enabling more accurate comparisons across alternatives during early design stages.

4.1.3. BLCA-AI integration

In recent years, Artificial Intelligence (AI) has gained considerable attention across multiple sectors, including the construction industry, as a transformative technology capable of accelerating and improving design and analytical processes related to the life cycle of buildings, such as environmental impact assessment. Compared with more "traditional" digital technologies, such as BIM and 3D modelling, AI introduces a significant advancement in automation, enhancing not only the efficiency of production processes but also their accuracy and overall performance.

The integration of Artificial Intelligence (AI) and Building Life Cycle Assessment (BLCA) is emerging as a important approach to overcome the static nature and data-intensiveness of conventional LCA. Traditional BLCA frameworks often rely on predefined datasets and generic emission factors, which limit their ability to capture the dynamic variability of construction processes across different life cycle stages. AI-enabled approaches introduce predictive modeling, real-time data processing, and optimization techniques that enhance both the accuracy and efficiency of environmental assessments, as shown in Fig. 10 [72].

Recent contributions highlight how deep learning and optimization algorithms can dynamically predict carbon emissions during construction and operational phases, providing more precise assessments compared to static LCA tools [73]. Xu [72] demonstrated that AI-enhanced frameworks achieved an R^2 of 0.92 between predicted and observed emissions, ensuring alignment with real-time data from IoT

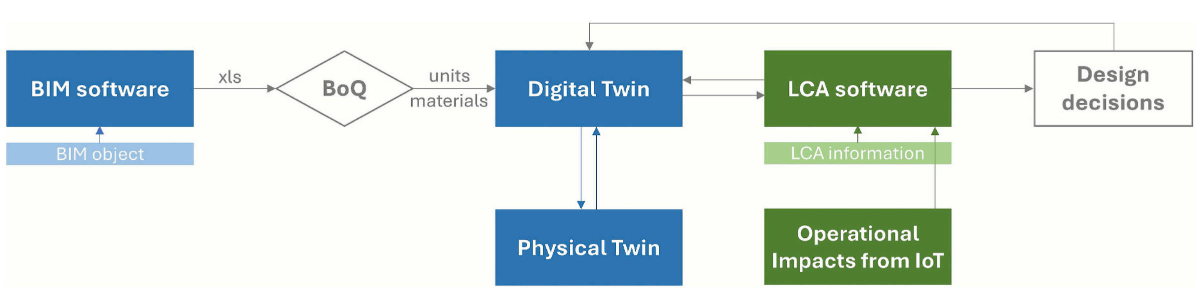

Fig. 9. Flowchart of the BLCA-DT integration which supports design decisions through real time interaction between Physical Twin and Digital one and Operational Impacts from IoT sensors coupled with LCA information to LCA software.

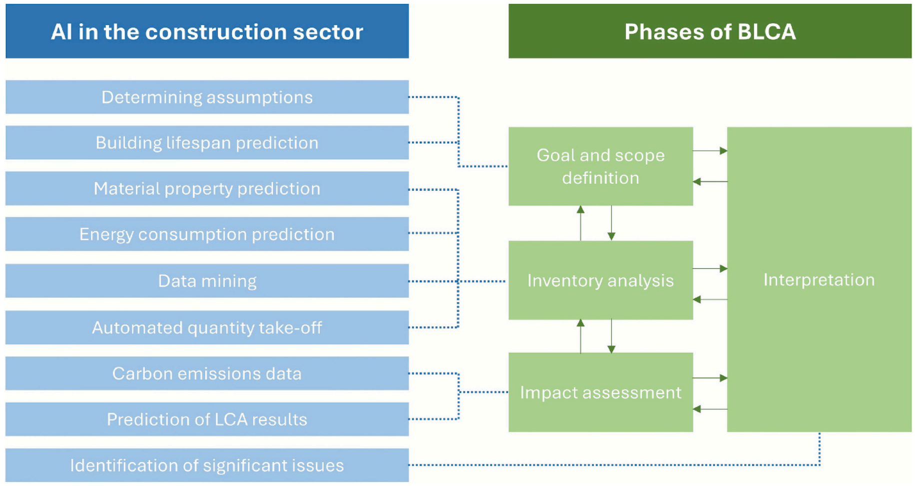

Fig. 10. Flowchart contributes of AI in each LCA phase.

sensors and BIM platforms. Such adaptive systems enable stakeholders to track emission spikes, evaluate alternative scenarios, and implement mitigation strategies with greater confidence.

A critical element emerging from recent studies is that any AI-LCA predictive framework depends on the construction of a robust, well-structured dataset, capable of representing the relationships between material quantities, construction processes, environmental context, and resulting impacts. The literature underscores that model performance is tightly linked to data quality, completeness, and consistency. Building such datasets typically requires integrating heterogeneous sources, including BIM models and bills of quantities, which provide material quantities and geometry; standardized LCA databases and environmental product declarations supplying emission factors; operational data streams from sensors for real-time monitoring; and historical project records that enable supervised learning approaches. For example, Ji et al. [74] built life-span prediction models using over 1.8 million building records, demonstrating the importance of large-scale datasets for reliability.

AI is also reshaping the Life Cycle Inventory (LCI) phase, historically regarded as one of the most resource-intensive stages of BLCA [75]. Text-mining and natural language processing algorithms have been developed to automate the extraction of material data from bills of quantities, reducing data collection time by up to 90 % while improving consistency in material classification [76]. This automation reduces a key bottleneck in LCA workflows, particularly in cases where BIM data are incomplete or inconsistent.

Machine learning techniques have been increasingly deployed to enhance prediction and optimization within BLCA. Jalota and Ayazi [77] reported that regression-based models, including random forests and gradient boosting, are particularly effective in predicting carbon emissions and optimizing material choices, while ensemble and hybrid methods improve robustness. Similarly, Martínez et al. [78] emphasized the role of deep learning in accelerating low-carbon material discovery and environmental benchmarking, highlighting its potential to guide sustainable material innovation while acknowledging the challenges of data integration and model generalization.

From an application-oriented perspective, AI-driven models have been used to predict building life spans, enabling more accurate estimations of both life cycle costs (LCC) and environmental impacts. Ji et al. [74] demonstrated that deep neural networks can predict building lifespans with high accuracy, reducing uncertainty in long-term impact assessments. Furthermore, integrated frameworks merging AI, BIM, and LCA have been shown to assist architects during early design stages, offering real-time carbon footprint estimates and design optimizations [79]. Case studies by Płoszaj-Mazurek showed that combining ML, large language models (LLMs), and BIM can guide decision-making and reduce embodied emissions in conceptual design [80].

AI integration into BLCA marks a paradigm shift from static, retrospective assessments to dynamic, predictive, and optimization-oriented frameworks. By enhancing data collection, predictive accuracy, and design support, AI enables more effective management of environmental impacts across the entire building life cycle, paving the way for scalable and adaptive strategies toward carbon–neutral construction [81].

4.1.4. BLCA-other DTs integration

In addition to BIM, DT, and AI, the literature also discusses the integration of BLCA with other digital technologies, most notably the Internet of Things (IoT), Geographic Information Systems (GIS), blockchain, and Virtual/Augmented Reality (VR/AR). Although these types of integration are less widespread than those examined in earlier sections, they offer valuable insights into how LCA methodologies can be applied across diverse contexts and operational conditions throughout a building's life cycle.

The combination of BLCA and IoT, for example, enables the connection of multiple devices within a shared digital network, facilitating the real-time collection of performance and environmental impact data from buildings and their components. Such continuous monitoring allows for more accurate quantification of carbon emissions and other environmental indicators, while accelerating and simplifying data acquisition processes [8283].

GIS-based integrations offer a spatially explicit perspective on BLCA, enabling the assessment of environmental impacts in relation to geographic conditions, local resource availability, transportation distances, and context-specific construction practices. By embedding life-cycle inventory data into geospatial databases, GIS can support location-sensitive modelling of embodied and operational impacts. This spatial integration is particularly valuable in early design stages, where location-driven environmental trade-offs can influence material selection, system sizing, and construction logistics [84].

The use of blockchain in BLCA is still in its early stages, yet it offers significant potential for improving data transparency, traceability, and reliability throughout the building life cycle. Blockchain-based systems enable secure and immutable recording of environmental data, material provenance, and compliance information across the supply chain. This ensures that LCA datasets, often criticized for their variability and lack of verification, can be authenticated, shared, and audited with higher confidence [28 85].

VR and AR technologies integrate BLCA by improving the communication and visualization of environmental impacts throughout design and decision-making processes. Through immersive simulations, stakeholders can interact with digital building models while receiving real-time feedback on embodied and operational impacts associated with materials, systems, and design alternatives. AR applications, in particular, allow users on construction sites to overlay environmental data directly onto physical components, supporting more informed decisions during installation, retrofitting, or maintenance. These tools are especially valuable for engaging non-expert stakeholders, enabling intuitive interpretation of LCA results and fostering greater awareness of low-carbon strategies [84].

4.2. Qualitative analysis

The quantitative analysis focused on the three integration types overview, while the qualitative one presents, in this section, an in-depth analysis conducted to address the second Research Question of the study (RQ2): "How can these integrations boost the decarbonization process of the construction sector?".

The SWOT (Strengths, Weaknesses, Opportunities, and Threats) analysis, a widely adopted method in scientific research for identifying internal (i.e., strengths and weaknesses) and external (i.e., opportunities and threats) factors that can either enable or hinder a given process, has been used to qualitative review the results of the study and to also support the development of a multidimensional understanding from various stakeholders' perspectives.

The discussion of the overall results of the qualitative analysis is presented in Section 5, Discussion, to investigate all the combinations of the SWOT analysis and explain all the key insights emerging from the three selected BLCA–BDTs integrations.

5. Discussion

The SWOT analysis of the three BLCA-BDTs integrations offers a multidimensional understanding of the benefits, limitations, and implementation challenges related to each technology. The critical discussion of the SLR results allows the identification of significant opportunities for improving the quality, transparency, and automation of environmental assessments in the construction sector. The qualitative analysis results for all the possible combinations of BLCA-BDTs integrations with SWOT factors are summarized and presented in Table 4.

BIM stands out for its ability to support early-stage sustainability decisions and provide real-time information on BLCA outcomes [86,87]. DT integration introduces features for dynamic modelling and continuous monitoring, which are particularly useful for addressing the building performance throughout its life cycle [88]. AI adds a new layer of data integrity and traceability, supporting trust among stakeholders and ensuring secure information flows throughout the BLCA process [89].

However, these advantages are counterbalanced by a series of shared and technology-specific weaknesses. Low interoperability, data fragmentation, and the immaturity of digital infrastructures remain critical barriers to the integration of BDTs with BLCA.

For instance, BIM models often lack the level of detail and semantic consistency required for automated LCA, while DT and AI suffer from high technical complexity, limited standardization, and significant financial or organizational constraints [28]. Opportunities emerge particularly in terms of improving data-driven decision-making, automating LCA workflows, and enabling more accurate and efficient assessments. Yet, several threats persist, including the lack of common data models, risks of data inconsistency across stakeholders, and, in the case of AI, potential negative environmental impacts due to energy-intensive operations.

5.1. Proposed guidelines and checklist

The main findings from the SLR and SWOT analysis led to the development of four strategic guidelines and the corresponding practical

Table 4
Qualitative analysis results of the BLCA-BDTs integration through SWOT representation.

Type of integration	Qualitative analysis	
BLCA-BIM integration	**S**	Automates data transfer between BIM models and LCA tools, eliminating manual re-entry and enabling real-time evaluation of environmental impacts [4]. Provides a comprehensive representation of the whole building, supporting intuitive and user-friendly BLCA workflows within BIM environments [54]. Allows early-stage environmental assessments, enabling designers to compare alternatives when design decisions still have a major impact on embodied carbon outcomes [52]. Supports iterative design processes through continuous feedback loops, automatically updating LCA results after each modification of the BIM model, without rerunning the entire assessment [90].
	W	Limited interoperability and weak semantic alignment between BIM schemas and LCA databases hinder seamless data exchange and automation of assessment workflows [91]. BIM object classes are not fully compatible with the structure and data requirements of LCA inventories, restricting the possibility of achieving fully automated BLCA processes [37]. Early-stage BIM models often lack sufficient detail on component types, material quantities, and dimensions, reducing the accuracy and completeness of preliminary LCA calculations [92].
	O	Direct extraction of project data from BIM models enhances both efficiency and accuracy of Life Cycle Inventory (LCI) data acquisition for BLCA workflows [86]. Integration of BIM with LCA supports comprehensive operational analyses, enabling the evaluation of energy performance and efficiency across the entire building life cycle [93]. BIM-based design workflows allow rapid comparison of multiple design alternatives at early stages, supporting more informed and sustainability-oriented decision-making [94].
	T	Absence of standardized semantic alignment between IFC schemas and LCA databases creates significant barriers to reliable data exchange between BIM platforms and LCA tools [52]. Fragmented data contributions from multiple stakeholders across the building lifecycle increase the risk of inconsistencies or outdated information, potentially compromising the robustness and accuracy of BLCA results [94].
BLCA-DT integration	**S**	Enables real-time data visualization, continuous monitoring and predictive modelling, increasing the dynamism, accuracy and responsiveness of LCA workflows [28]. Enhances data security, integrity and transparency across the lifecycle, strengthening stakeholder trust and improving the reliability of environmental information flows [84]. Supports self-learning and adaptive system capabilities, enabling progressively more accurate performance assessments through iterative data enrichment over time [71].
	W	Persistent interoperability limitations, intellectual property concerns, data uncertainty and connectivity constraints reduce the robustness and scalability of DT–LCA integrations [71]. Real-time digital replicas require advanced algorithms and substantial computational resources, making accurate simulation and continuous feedback loops technically complex to implement [4]. Effective integration of DT within BLCA frameworks depends on multidisciplinary expertise, posing organizational and operational challenges for widespread adoption [66].
	O	Enables data-driven decision-making by reducing resource inefficiencies and improving the overall understanding of a project's environmental footprint [84] Facilitates the adoption of innovative construction methods by simulating detailed building performance and supporting

(continued on next page)

Table 4 (*continued*)

Type of integration		Qualitative analysis
		dynamic assessments of energy efficiency and flexible design options [95]. Allows the integration of dynamic operational data, such as occupancy patterns and appliance usage, enhancing the accuracy and realism of environmental impact assessments [66].
	T	Dependence on synchronized data streams from sensors, IoT systems and BIM models increases vulnerability to inconsistencies, delays or incomplete data, which can significantly compromise the reliability of LCA results [96]. Widespread use of proprietary data structures and non-standardized information models in DT implementations limits interoperability with LCA tools and environmental databases, reducing the scalability of integrated workflows [66].
BLCA-AI integration	**S**	Increases the accuracy of carbon emission predictions by up to 20 % compared to traditional LCA methods [82]. Uses NLP techniques to automate extraction of material data from Bills of Quantities, reducing data collection time by up to 80–90 % [76]. Processes real-time data from sensors and digital models, achieving over 90 % alignment between predicted and observed emissions [72]. Supports early-stage sustainability evaluations through AI–BIM–LCA tools, enabling rapid environmental assessment during conceptual design [97]. Accelerates the identification and evaluation of low-carbon material alternatives through deep learning approaches [98].
	W	Limited availability of standardized and high-quality datasets reduces the reliability and generalizability of AI-based LCA models [99]. High computational demands for training and deploying advanced algorithms, especially deep learning models, limit their practical scalability [97]. Low interpretability of "black-box" AI models complicates validation and undermines stakeholder trust in the resulting environmental assessments [100]. Absence of common standards for AI–LCA integration leads to fragmented, non-replicable and non-interoperable methodological approaches [101]. Strong dependence on large and complete historical datasets, often unavailable for novel construction projects or emerging low-carbon materials [73].
	O	Enables the development of dynamic and adaptive LCA models capable of updating in response to real-time variations in project conditions or site data [102]. Supports the expansion of environmental assessment frameworks toward urban platforms and smart cities, enabling integrated carbon-emission management at district or city scale [29]. Facilitates the use of generative AI and large language models (LLMs) as virtual design assistants, enhancing decision-making and stakeholder support throughout the building lifecycle [96].
	T	AI models trained on incomplete or biased datasets risk producing misleading or unreliable environmental predictions, undermining assessment quality [102]. Limited transparency and explainability of many AI methods contribute to resistance among practitioners and reduce trust in AI-supported LCA outputs [99]. Dependence on advanced digital infrastructures, such as cloud platforms and high-performance computing, may limit adoption among SMEs due to cost and accessibility constraints [29]. Ethical and regulatory concerns related to data governance, privacy and responsible AI use may slow the deployment of AI-driven assessment systems in the construction sector [99].

checklist clustered around four main fields as summarized in the Sankey diagram in Fig. 11: A. Design process, B. Common language, C. Tools, and D. People, for leveraging BLCA-BDTs integrations towards the Zero Emissions Building (ZEB) target for the construction sector.

A. Design process: fostering early-stage integration of BLCA in design workflows
- The SLR highlighted how environmental performance evaluations are still frequently treated as late-stage compliance checks, limiting their influence on critical project decisions.
- Incorporating LCA and resource impact evaluations during the early design phase enables project teams to test structural systems, material options, and building procedures, maintaining the possibility to evaluate different options with minimal cost implications.
- Official project documents should specify minimum environmental performance targets (such as embodied carbon thresholds per m2) alongside functional and budgetary requirements.
- Digital models and objects should be designed to include data required for a complete LCA, including preliminary Bills of Quantities (BoQ), provisional material specifications, and transportation assumptions.
- Parametric modelling and plug-ins can support scenario analyses to rapidly compare low-carbon design alternatives, while defining clear Levels of Development (LOD) at each phase ensures that data quality improves progressively as design choices are made.

B. **Common language: developing shared data standards**
- A persistent challenge in BLCA-BDTs integration is the misalignment between element descriptions, lifecycle boundary conditions, and classification systems used by different tools and stakeholders. Without standardized vocabularies and protocols, the automation of data exchange among digital environments and LCA tools is limited, increasing manual workloads and error risks. Numerous digital modelling languages and data interchange standards are currently employed in the construction sector.
- Stakeholders should align their workflows with recognized classification frameworks (e.g., Uniclass, OmniClass) and co-develop digital material libraries that systematically link digital object properties to third-party verified EPDs or standardized LCA datasets. This alignment guarantees the credibility and traceability of environmental data integrated into digital objects during all the life cycle phases of the building.
- LCI requirements should be specified in BDTs execution plans – such as BIM Execution Plan (BEP) and Digital Twin Execution Plan (DTEP) – to define who provides which environmental attributes, when, and in which format, and to facilitate the use of a verified datasets to support compliance with various sustainability and environmental certifications.

C. **Tools: investing in secure and collaborative digital infrastructures**
- In the construction sector, most of the projects present fragmented workflows between proprietary design tools, disconnected databases and isolated sustainability assessment. There is an emerging need to enhance tools and infrastructures to guarantee that BLCA can be continuously integrated and updated within secure, collaborative digital ecosystems.
- Cloud-based common data environments with open APIs have to be used to facilitate consistent data sharing, version control and stakeholder access rights throughout the building lifecycle.
- Blockchain-based solutions can be used to ensure traceability and trust by securing material passports, verifying the authenticity of EPDs data, and automating smart contracts associated with sustainability performance.
- Real-world test beds and living labs can accelerate the validation of these integrated digital infrastructures by demonstrating the feasibility of semi-automated or fully automated workflows within operational project constraints.

D. **People: promoting interdisciplinary training on B(LCA-DTs) integration**
- The success of BLCA-BDTs integration depends on the skills and collaborative capability of those who will implement it, but the

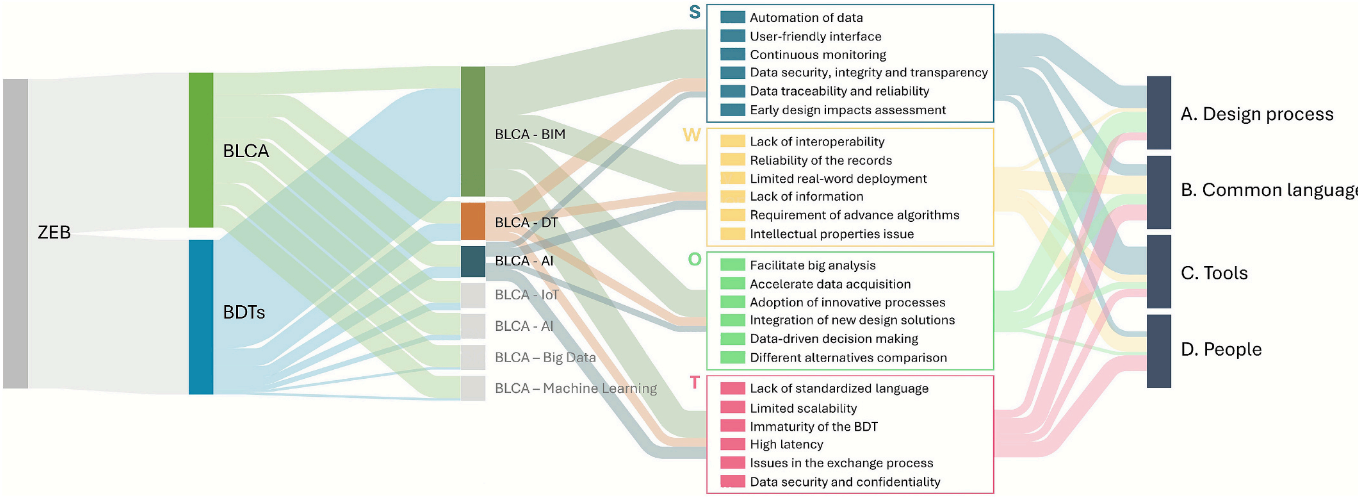

Fig. 11. Sankey diagram illustrating the methodological workflow adopted in this study to identify guidelines about BLCA-BDTs integration process.

current professional practice still lacks the interdisciplinary knowledge needed to manage the technical and procedural aspects of BLCA-BDTs integration. Specific learning programs for emerging digital workflows of BLCA are recommended for professionals, and software house companies can support this best practice by offering in-house training, practical workshops, and promoting interdisciplinary instruments that combine digital modelling with environmental analysis.

- Identification of a project-specific BLCA coordinator to serve as a reference person for ensuring sustainability goals and digital processes are linked throughout the design and construction phases.
- Multi-stakeholder networks – involving academia, standardization bodies, software developers, and contractors – should collaborate to identify best practice recommendations and an open-access knowledge database.

To ensure the transposition of the proposed guidelines into daily practice, authors developed a corresponding checklist (Fig. 12) to provide practical verification questions for all stakeholders involved in the building value chain to effectively assess BLCA-BDTs integration towards carbon neutrality target.

6. Conclusions

The starting point of this study is the EU decarbonization target for the construction sector, which can be boosted by the integration of some of the already in use and diffuse methodologies and technologies to assess the environmental impacts in an interoperable and digitized way: Building Life Cycle Assessment (BLCA) and Building Digital Technologies (BDTs). The study aims to analyse, by a Systematic Literature Review (SLR), the most efficient integrated solutions to facilitate their application within the building design and construction value chain,

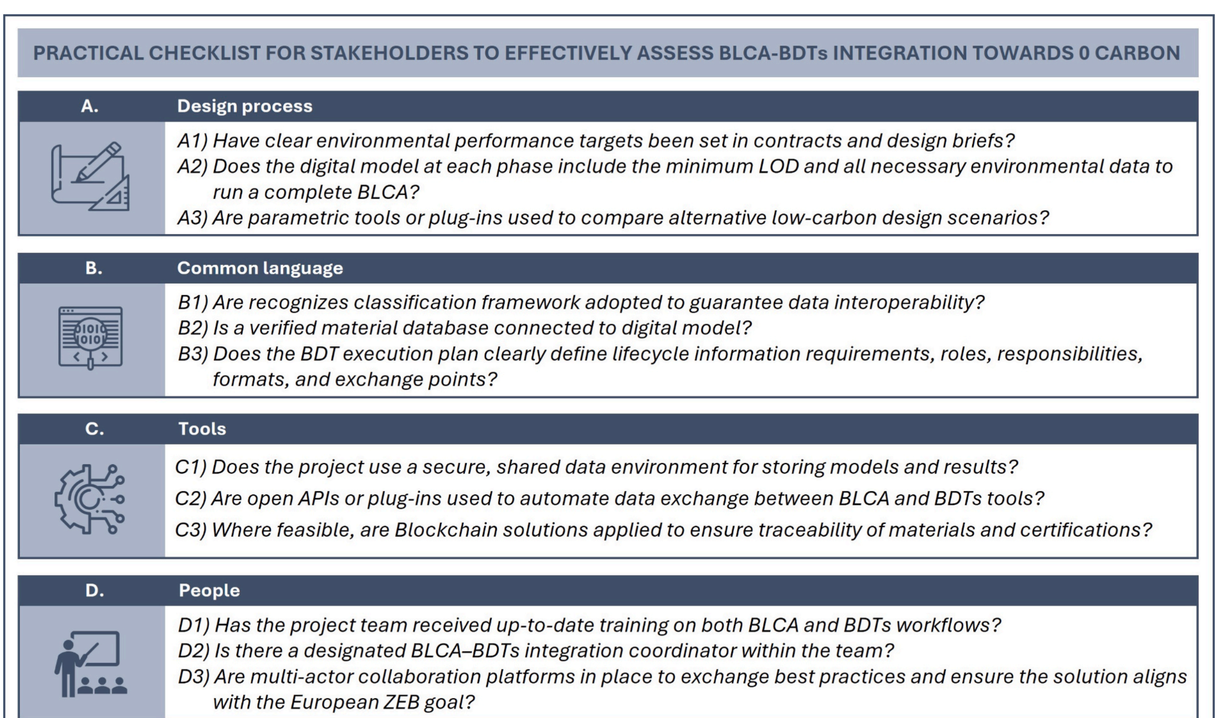

Fig. 12. Practical checklist for stakeholders to assess effectively BLCA-BDTs integration with key field questions.

with the final scope to reach the above-mentioned target of carbon neutrality.

The SLR results have been examined through a dual analysis: qualitative and quantitative, to answer the RQs:

RQ1: "Which are the most common BLCA–BDT integrations in the construction sector?".

RQ2: "How can these integrations boost the decarbonization process of the construction sector?".

RQ3: "How can different target groups use these integrations to boost the decarbonization process of the construction sector?".

The quantitative analysis, which allow to answer to the RQ1 and identify the three main digital technologies – Building Information Modelling (BIM), Digital Twins (DT), and Artificial Intelligence (AI) – integrated with BLCA, coupled with the qualitative analysis, conducted using a SWOT framework, which answered to the RQ2 by highlighting how such integrations can effectively contribute to boost the EU decarbonization goals, to improve data accuracy, traceability, and efficiency of environmental assessments.

Referring to the SWOT results for each type of BLCA-BDTs integration, the authors indicated that:

- BLCA–BIM integration primarily supports the automation of data flows and enables iterative environmental assessments from the early design stages, where design alternatives can be rapidly compared and adjusted. It strengthens real-time feedback loops, reduces manual rework, and improves the reliability and consistency of lifecycle calculations by leveraging user-friendly BIM environments already used in practice.
- BLCA–DT integration makes it possible to monitor, visualize, and predict building performance continuously throughout the entire lifecycle, extending BLCA beyond static calculations. By connecting sensor networks, IoT systems and virtual models, DT frameworks allow dynamic assessments of operational impacts and support data-driven decision-making, which can guide innovative construction methods and adaptive management strategies.
- BLCA–AI integration introduces advanced predictive and optimization capabilities into environmental assessments, automating data collection, filling information gaps, and enhancing the accuracy of life cycle models. By applying machine learning and natural language processing, AI supports early-stage design evaluations, material optimization, and dynamic scenario analysis, thereby reducing uncertainty and enabling faster, data-driven sustainability decisions across the building lifecycle.

Despite these specific strengths, the SWOT analysis confirms that persistent challenges remain for all three integration types, including a lack of full interoperability, insufficient standardization, fragmented ontologies, and a technological immaturity of certain solutions, especially in the case of AI applications. These limitations currently hinder the widespread deployment and scalability of fully automated BLCA workflows and highlight the need for further development, harmonization, and practical testing to enhance the decarbonization potential across the construction sector.

A comprehensive set of guidelines, based on the SLR and SWOT results of this study, has been developed to answer the RQ3 and to promote the BLCA-BDTs integration and to address the identified barriers that limit their application and use between different stakeholders across the entire building value chain. The proposed guidelines are clustered around four main fields, emerging as fundamental aspects of the topics studied: A. Design process, B. Common language, C. Tools, and D. People.

6.1. Challenges and limits of the study

The review highlights several challenges that limit the effective integration of BLCA with well-known and emerging digital technologies. Current research remains fragmented, with heterogeneous methods, inconsistent system boundaries, and limited standardization, which reduces comparability across studies. Data availability and quality continue to be obstacles: many approaches rely on static, incomplete, or non-interoperable datasets, limiting the potential of BIM-, DT-, and AI-enabled assessments to operate dynamically or in real time. Moreover, the implementation of these technologies often requires advanced expertise and computational resources, creating a gap between experimental applications and their practical adoption in real projects.

In addition to these sector-wide challenges, this study presents some limitations. The review is hinder by the selection criteria and by the uneven maturity of the available literature, particularly regarding BLCA–AI and BLCA–DT integrations. Some technologies are still at an early stage, with few validated case studies, reducing the possibility of a comprehensive assessment of their long-term performance. Furthermore, the reliance on reported results limits the ability to evaluate the replicability and robustness of the proposed workflows.

6.2. Future research insights

While this study provides a comprehensive overview of the integration between BLCA and BDTs, some aspects deserve further exploration in future research. The choice to focus on peer-reviewed literature ensures the scientific robustness of the findings, though it may exclude valuable insights from grey literature or unpublished industrial reports. Furthermore, the proposed classification of integration types is based on current literature and may evolve as technologies mature. Finally, the SWOT analysis presented relies on expert interpretations of the reviewed works and could be further refined through stakeholder consultation.

Future research should focus on empirically testing integrated BLCA workflows in real-world building projects, particularly for DT technology. Moreover, further efforts are needed to develop open-source platforms, semantic data standards, and AI-driven decision-support systems that can fully automate and contextualize the BLCA process. Cross-disciplinary collaborations between academia, industry, and public authorities will be essential to bridge existing gaps and ensure the operational implementation of digital BLCA in support of energy-efficient, low-impact, and future-proof buildings.

CRediT authorship contribution statement

Marta Maria Sesana: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Formal analysis, Data curation, Conceptualization. **Paolo Dell'Oro:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation. **Graziano Salvalai:** Writing – review & editing, Validation, Supervision, Conceptualization. **Helena Gervasio:** Validation, Supervision, Conceptualization.

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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.

Appendix

Application of BLCA-BIM integration in literature

Authors	Location	Building type	LCA phases considered	Type of BLCA-BIMintegration	LCA software	BIM software
Zheng et al.(2025) [57]	China	Residential	A1-A3, A4-A5	1;2;3;4	Dynamo; SimaPro	Revit
Rodriguez et al. (2025) [33]	Spain	Factory	A1-A3, A4-A5, B1, B6, B7	1;2	SimaPro; Athena	Revit
Mohammed et al. (2025) [11]	Egypt	Factory	A1-A3, A4, B2-B5, C2-C4; D	4	e-tool; Tally	Revit
Masoumi-Hajiagha et al. (2025) [103]	Iran	Laboratory	–	4	Dynamo	Revit
Nasir et al. (2025) [104]	India	Office	A1-A3, A4, A5, B6-B7, C1-C4	1	Excel VBA LCA module	Revit
Yardimci et al. (2024) [105]	Turkey	Residential	A1-A3, A4, B2-B5, C2-C4, D	4	Tally	Revit
Lima et al. (2024) [106]	Portugal	Residential	A1-A3, A4, B4-B5, B6, C3-C4, D	4	One Click LCA	Revit
Han et al. (2024) [25]	China	Residential	C1-C4, D	4	Dynamo; e-tool	Revit
Soust-Verdaguer et al. (2023) [107]	Spain	Residential	A1-A3, A5, C1-C2, C4	5	BIM3LCA (tool developed by the authors)	Revit
Mowafy et al. (2023) [108]	Egypt	Residential	A1–A3, A4, B4, B6, C3–C4, D	3	Honeybee/EnergyPlus for operational; Bombyx (KBOB DB) for embodied LCA	Revit; Rhino / Grasshopper
Li et al. (2023) [109]	China	School	A1-A3, A4, A5, B4, B6, C4, D	4	IBLAT (tool developed by the authors)	Revit
Klumbyte et al. (2023) [49]	Netherlands	Residential	A1-A3, A4-A5	2	One Click LCA	Revit
Boje et al. (2023) [66]	Luxembourg	Office	–	2	Brightway2	–
Yeung et al. (2023) [31]	UK; Luxembourg	Univeristy	A1-A3, A4, A5, B6	3	Brightway2	ArchiCAD; Revit
Di Santo et al. (2023) [91]	Italy	Residential	A1-A3, B1-B6, C1-C4	1	Active House LCA	Revit
Heydari et al. (2023) [110]	Iran	Office	A1-A3, A4, A5	4	Dynamo	Revit
Viscuso et al. (2022) [58]	Italy	Office	–	4	One Click LCA	Revit
Kamari et al. (2022) [37]	Denmark	Residential	A1-A4	4	One Click LCA	Revit
Bouhmoud et al. (2022) [111]	Morocco	Residential	A1-A5, B6, C1-C4	3	BLCCE	Revit
Cheng et al. (2022) [112]	China	Sport center	A1-A3, A4, A5, C1-C4	1	Custom LCEEI calculator	Revit
Dauletbek et al. (2022) [113]	China	Dormitory	A1–A3, A4, B4, B6, C3–C4	1	WEBlca	Revit
Alwan et al. (2022) [114]	UK	Residential	A1-A3, A4, A5, B1-B5, C1-C4	2	Carbon benchmarking tool (pycab) (tool developed by the authors)	ArchiCAD
Xu et al. (2022) [44]	China	Residential	A1-A3, A4, A5	2	SimaPro	Revit
Kylili et al. (2021) [115]	Cyprus	Residential	A1-A3	1	EcoHestia	Revit
Ansah et al. (2021) [12]	China	Residential	A1-A3, A4, A5, B2, B4, B6, C1-C4	5	Dynamo	Revit
Tushar et al. (2021) [56]	Australia	Residential	–	4	Tally	Revit
Su et al. (2020) [116]	China	Residential	–	3	BEPAS	Revit
Santos et al. (2020) [117]	Morocco	Mixed-use	A1-A3, A4, A5, B2–B6, C2–C4, D	5	BIMEELCA	Revit
Horn et al. (2020) [118]	Germany	School	A1–A3, B4, B6, C1-C4, D	5	GENERIS	Revit
Santos et al. (2019) [52]	Belgium	Residential	–	5	Custom BIM-integrated LCA/LCC tool	Revit
Veselka et al. (2019) [59]	Czech Republic	Residential	A1-A3	5	ENVI-MAT	Revit
Cavalliere et al. (2019) [119]	Germany	Residential	A1-A3, B4, C3-C4	3	KBOB Okobilanzaten	Rhinoceros
Yang et al. (2018) [120]	China	Residential	A1-A3	3	eBALANCE	Revit
Nizam et al. (2018) [41]	China	–	A1-A3, A4, A5	5	Custom Revit API tool	Revit
Najjar et al. (2017) [121]	Finland	Residential	A1-A3, A4, A5	1	Athena Impact Estimator	Revit
Shadram et al. (2016) [122]	Sweden	Residential	A1-A3, A4	3	PowerPivot; Custom LCA engine	Revit

Data availability

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

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