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Stakeholder perspectives on BIM–LCA integration in building design: Adoption, challenges, and future directions

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ABSTRACT

Europe's ambitious net-zero carbon targets compel the AEC sector to quickly adapt. Mandatory whole-life carbon declarations will require stakeholders to quantify and reduce environmental impacts using Life Cycle Assessment (LCA). However, LCA is widely perceived as complex, time-consuming, and costly. Building Information Modelling (BIM) has the potential to streamline LCA processes (e.g., quantity take-off). Research on BIM-LCA integration has grown substantially since 2013, but the extent of its adoption in practice remains unclear, as the perspectives of end-users have been largely overlooked.

This study addresses this gap by assessing BIM-LCA adoption and end-user challenges through a mixed-methods approach: a survey of 62 stakeholders and a focus group with six LCA specialists.

Results show that while 82% of participants apply sustainability strategies, only 45% have experience with LCA, and just 29% use BIM-LCA tools. LCA is most often conducted at late design stages, primarily to comply with certification requirements. Barriers reported include the lack of comprehensive environmental databases, limited interoperability, demanding information requirements, repetitive manual tasks (e.g., BoQ edition and mapping BIM and LCA data), lack of an interactive process (real-time feedback), and limited support for result interpretation. Participants expressed strong interest in early-stage parametric modelling, continuous performance monitoring, real-time BIM synchronisation, and integrated multi-criteria decision analysis and multi-objective optimisation.

Beyond diagnosing challenges, this study identifies recent research developments addressing these issues and proposes priority actions for user-oriented BIM-LCA across four areas: Data & Standardisation, Automation & Digital Tools, Education & Skills and Decision Support methods.

1. Introduction

The Architecture, Engineering, and Construction (AEC) sector is one of the most significant contributors to environmental impacts in Europe. Activities related to building's lifecycle account for approximately 36% of greenhouse gas emissions and 40% of total energy consumption [1]. As a result, the AEC sector plays a central role in the European Union's strategy to achieve climate neutrality by 2050 and become the world's first climate-neutral continent [2].

Policy frameworks at both national and EU levels are driving the AEC sector towards this goal. Over the last decade, regulatory efforts and incentive mechanisms have primarily focused on reducing operational energy demand, aiming to transition to near-zero energy buildings by 2020, as mandated by the Energy Performance of Buildings Directive (EPBD). These efforts have led to the construction of high-performance buildings with very low energy demand; such performance is anticipated to become increasingly common in new construction and retrofitting practices across Europe. According to Passer et al. [3], the potential for further optimisation in low-energy buildings is expected to be marginal.

Following the 2024 EPBD recast, attention has shifted towards a whole-life carbon approach, aiming for zero-emission buildings, rather than merely near-zero, by 2030 [4]. This includes not only operational but also embodied impacts, which represent 20–25% of all lifecycle emissions of buildings that meet current energy performance regulations [5]. Most of these will be emitted within the first few years of a building lifecycle and, if not accounted for, may undermine carbon savings achieved through operational energy efficiency.

The recommended methodology for assessing the potential environmental impacts throughout a product's lifecycle, from raw material

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extraction to end-of-life, is the Life Cycle Assessment (LCA), as defined in ISO 14040-14044 series [6,7]. LCA includes four key phases: 1) Goal and Scope Definition, which establishes the study's purpose, reference period, functional unit, and system boundaries; 2) Life Cycle Inventory (LCI), focused on quantifying inputs/outputs across the lifecycle; 3) Life Cycle Impact Assessment (LCIA), which converts inventory data into environmental impact indicators through classification and characterisation using methodologies like ILCD, EF 3.0, CML, ReCiPe, or TRACI, and 4) Interpretation of results.

International and European standards by ISO/TC 59/SC 17 [8–10] and CEN/TC 350 [11–13] along with guidance from institutions like the Royal Institution of Chartered Surveyors (RICS) [14] have supported the harmonisation of Building LCA.

Building LCA can be applied at various levels, from materials and products to entire buildings and neighbourhoods. It is commonly used as both a reporting tool and a means to obtain product environmental labels (e.g., Environmental Declarations Type III, also known as Environmental Product Declarations - EPDs), Green Building Certifications (GBCs), and, more recently, to meet mandatory carbon footprint regulations for buildings.

Regarding the latter, the 2024 recast of the EPBD introduced a mandatory requirement for declaring Global Warming Potential (GWP) throughout the building's lifecycle [6]. Starting in 2028, all new buildings over 1,000 m^2 must report their GWP following the Level(s) framework guidelines.

Several member states adopted whole-life carbon policies and are developing roadmaps to introduce GWP limits for new buildings [15]. Germany, the United Kingdom, and Switzerland mandate LCA in public procurement, although no specific limit values have yet been established. On the other hand, Denmark introduced a limit of 12 kg CO_2e/m^2/year for large new buildings in 2023, which will tighten to 7.1 kg CO_2e/m^2/year by 2025 [16]. Although expressed as annual values, these limits represent not only operational carbon but also the average annualised embodied carbon over a 50-year reference period. Similarly, in France, a new apartment building must be within a maximum threshold for greenhouse gas emissions from energy consumption of 14 kg CO_2e/m^2/year, and within a maximum construction-related emissions threshold of 740 kg CO_2e/m^2 [16].

Building LCA will no longer be optional, and ensuring compliance will require AEC stakeholders to acquire appropriate skills and understanding of its methodology. To be effective, LCA should inform early design decisions—when changes are more cost-effective and impactful—rather than serve solely as a post-design documentation tool. However, LCI data collection and LCIA processes are data-intensive, manual, error-prone, and time-consuming, making conventional Building LCA inefficient for early and continuous monitoring of environmental impacts throughout the design phase.

Recent studies have shown that integrating Building Information Modelling (BIM) and LCA can automate the time-consuming LCI and LCIA processes, especially when supported by structured data and shared ontologies [17]. In the context of BIM-based LCA, building products and processes can be extracted from BIM models during the LCI phase. In the LCIA phase, environmental impacts associated with each product/process are linked to the corresponding BIM quantities and aggregated to quantify the overall environmental performance of the building.

Several literature reviews have examined and categorised the benefits and limitations of BIM-LCA approaches. Safari et al. [18] identified three types of data extraction between BIM and LCA: conventional, static, and dynamic. In the conventional approach, the Bill of Quantities (BoQ) extracted from BIM models is manually or automatically entered into the LCA software. The static approach uses IFC, maintaining links to LCA data via global identifiers, allowing updates without re-mapping. The dynamic approach enables a bidirectional data flow, automatically updating LCA results when the BIM model changes, thereby supporting iterative design processes. Other authors [19–21], classified BIM-LCA according to the data exchange processes: 1) export BoQ into Excel, 2) export BoQ into a dedicated LCA tool, 3) use LCA add-ons for BIM software, 4) use visual programming languages (VPL), 5) use the IFC format for data transfer, and 6) include LCA data in BIM objects, using a library of BIM objects and materials with LCA data integrated as parameters.

Zheng et al. [22] assessed these BIM-LCA approaches, highlighting the trade-offs between accuracy and efficiency, whereas Tam et al. [21] proposed a method to select the optimal BIM-LCA integration approach for each design stage. Mora et al. [23], Teng et al. [24] and Lu et al. [25] identified key barriers, including issues related to the availability and quality of BIM model data, interoperability challenges, uncertainties in early design and the absence of standardised data structures to minimise manual processes. Seyis [26] complemented this distinction with an expert-based classification of advantages and disadvantages of current BIM-LCA tools. More recently, Parece et al. [17] synthesised recent developments in automation and decision-making in BIM-LCA tools, focusing on progress between 2019 and 2025.

While these systematic reviews provide a comprehensive overview of research progress and outline future directions, it remains unclear how these approaches are perceived by end-users and applied in real-world practice. Assessing current BIM-LCA adoption and understanding how professionals (e.g., LCA practitioners, architects, and engineers) perceive the usability, efficiency, and relevance of these tools in their workflows is essential to promote broader adoption and to guide future research towards user-oriented solutions.

While previous studies have explored BIM adoption in the AEC sector [27–31], research on stakeholders' perspectives regarding LCA adoption remains limited [32–35], especially on BIM-LCA [36–38]. Surveys by Schlanbusch et al. [37], Balouktsi et al. [38] and Abdelaal et al. [36] focused on assessing the BIM adoption to aid LCA, and on the perception of the benefits of these combined tools in a broader sense. They concluded that BIM-LCA remains limited in professional contexts, often due to low client demand for LCA, lack of training, limited interoperability, reliance on manual processes, and the overall cost of implementation.

As summarised in Table 1, no prior study has examined how the AEC industry perceives and uses BIM-LCA tools in Europe, or explored the specific challenges faced by end-users when using these combined tools and how they can be mitigated. To date, only one study—by Meex et al. [39,40] —has explicitly addressed end-user needs, proposing criteria to make BIM-LCA tools more accessible and architect-friendly during the early design stages.

Moreover, most of the existing surveys predate 2022. Given the rapid advances in automation and decision-support, coupled with the increasing regulatory demands across Europe, it is both timely and necessary to reassess the current state of BIM-LCA adoption and to examine how these emerging factors are reshaping professional practices.

The present study aims to address this gap through a mixed-methods approach, combining an online survey of 62 AEC stakeholders, including architects, engineers, contractors, and developers, with a focus group session involving 6 LCA practitioners. It seeks to answer the following research questions (RQ):

RQ1. What is the current level of BIM-LCA adoption in the AEC industry?

RQ2. What challenges do AEC stakeholders face when using BIM-LCA software during the design and decision-making processes?

RQ3. To what extent can the advances in BIM-LCA identified in previous literature reviews address the challenges faced by the AEC industry?

The user challenges identified through the survey and focus group are mapped against recent advances in a previous systematic review by

Table 1
Overview of previous surveys concerning LCA and BIM in the AEC sector.

Author	Year	Topic	Goal	Target group	Geographic scope	Questions On BIM-LCA	Participants	Main conclusions
Olinzock et al. [33]	2011/ 2012	LCA	Clarify the state of knowledge of LCA among AEC stakeholders	AEC stakeholders	United States	0/	250	• Lack of clients' demand • LCA was underutilised; only 33% have conducted an LCA
Han & Srebric [34]	2012/ 2013	LCA	Role of LCA and energy simulation in building design	Building designers	United States	0	96	• LCA is much less frequently used than energy simulations. • The designers with less than 10 years of work experience tend to be more likely to perform LCA in their projects.
Sibiude et al. [35]	2013/ 2014	LCA	LCA-related needs of AEC stakeholders for LCA tool developers	AEC stakeholders	France	0	121	• The inclusion of normalisation factors is preferred • Aggregation system is preferred with the possibility to modify the weighting
Jusselme T. et al. [32]	2020	LCA	Surveying LCA practice and context at early building design stages	Architects & engineers	Europe	0	495	• Lack of clients' requests for LCA results, • Low use of *LCA* software, • High practitioners' willingness to consider environmental constraints in their practice, • The cost of using *LCA* is the major issue.
Balouktsi et al. [38]	2020	LCA -BIM	Identify LCA's acceptance level and its current application in daily practice. Generic questions about the BIM role in building LCA	Architects & engineers	Global	1	1166 (Europe: 956)	• Lack of clients' requests for LCA results. • Lack of practitioner expertise • Only 9% use BIM-LCA, and 37% use QTO for cost estimation.
Schlanbusch et al. [37]	2015/ 2016	LCA-BIM	Knowledge gaps and issues in building LCA and generic questions about the role of BIM	AEC stakeholders	Nordic countries	2	57	• LCA is time-consuming and expensive. • Interest in creating a common Nordic LCA database, • Accounting for end-of-life phases is challenging • Weighting factors or discount rates in building LCA should be normalised • BIM-LCA was described as an opportunity in the early design
Abdelaal et al. [36]	2022	LCA-BIM	Stakeholders' perspectives on BIM and LCA for green buildings and generic questions about the role of BIM	AEC stakeholders	New Zealand	6	215	• 50% have no previous experience with either BIM or LCA. • Most participants agreed-upon the value of LCA for design decisions • BIM still perceive BIM as a visualisation tool • BIM-LCA is more commonly used to assess Operational impacts.
Meex et al. [39,40]	2014	BIM-LCA	Design-oriented user requirements for early design LCA tools (Survey + focus group)	Architects	Flanders (Belgium)	9	Survey 364 Focus group 10	• Criteria for architect-friendliness LCA and energy simulation tools is defined.

Parece et al. [17]. This study goes beyond diagnosis by proposing targeted actions to inform future research and drive user-oriented development of BIM-LCA, particularly in the areas of automation, decision support, standardisation, and regulatory alignment.

The study was approved by the Ethics Committee of ISCTE–University Institute of Lisbon.

The structure of the article is as follows: after this introduction, Section 2 describes the methodology adopted for the survey and focus group. Section 3 presents and analyses the results of the survey and focus group. Section 4 discusses the main results, highlighting current challenges and future research needs for user-oriented BIM-LCA. Finally, Section 5 presents the conclusions and outlines directions for future work.

2. Methods

This study follows a mixed-methods approach structured in three parts (Fig. 1): (1) a web-based survey, designed to evaluate the current adoption levels, perceived challenges, valued features, and decision-making practices related to BIM-LCA tools among European stakeholders; (2) an online focus group, held with experienced LCA professionals that explores critical challenges and enrich survey findings; (3) the empirical results from the survey and focus group are mapped against the findings of a systematic literature review (SLR) covering automation and decision-making in BIM-LCA research over the past five years [17]. This comparison enables a critical alignment between academic outputs and industry needs, supporting the identification of priority actions to advance user-oriented BIM-LCA development.

Sections 2.1 and 2.2 detail the methods used for the survey and focus group.

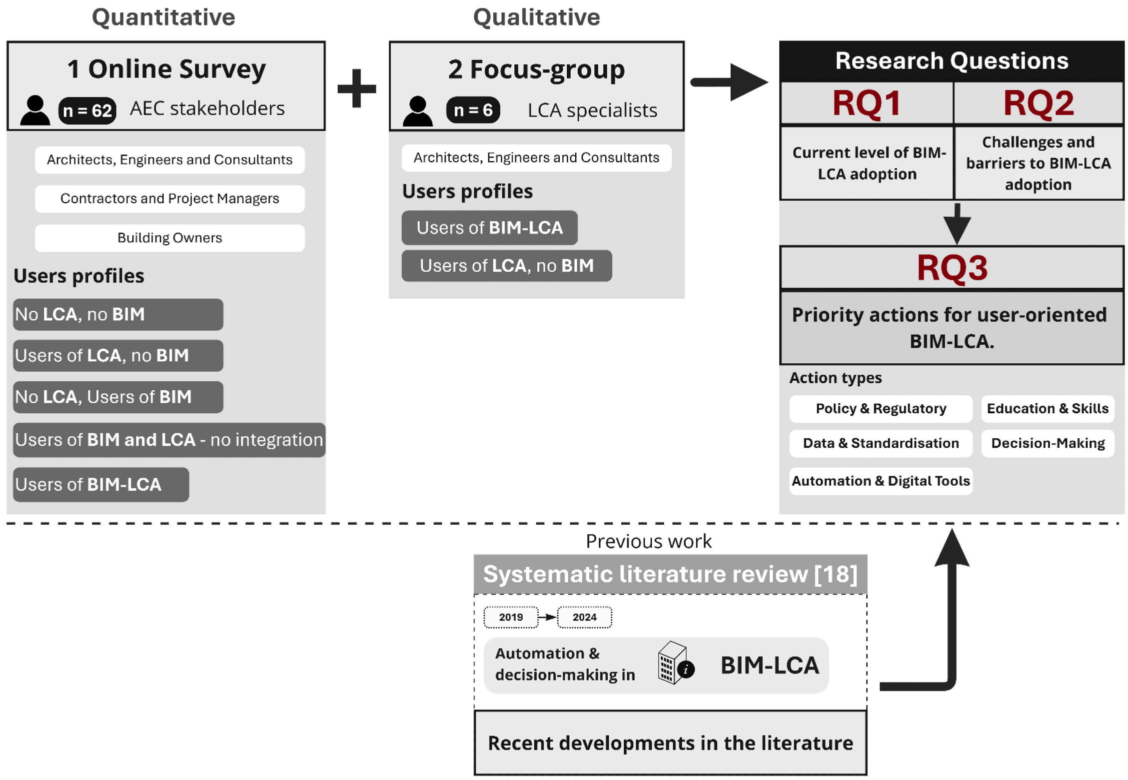

Fig. 1. Overview of the mixed-methods approach adopted in this study and its alignment with the research questions (RQs).

2.1. Survey design

2.1.1. Survey data collection

Data collection took place from October 2024 to January 2025. Participants were recruited via email, LinkedIn, and AEC sector professional events.

Eligible participants were professionals actively engaged in design, engineering, consultancy, project management, or contracting, and with some degree of practical knowledge or experience in sustainability-related practices within the AEC sector.

A total of 520 invitations were sent, and 62 valid responses were received, resulting in a response rate of 11.9%. While relatively low, this rate is consistent with similar studies, as web-based surveys targeting technical professionals typically report response rates between 5% and 20% [33]. The specialised nature of the topic—requiring practical knowledge of both sustainability and LCA—limited the eligible respondent pool.

2.1.2. Survey structure and logic

The survey used branching logic, ranging from 17 to 62 questions and taking 10–30 minutes to complete depending on participants responses. The survey contained four types of questions: (a) multiple-choice with a single answer, (b) multiple-choice allowing the selection of more than one option, (c) scale of importance, and (d) free-text responses. Most multiple-choice questions included an optional text field for participants to provide further detail or elaborate beyond the pre-defined options.

Scale of importance questions, two different Likert scales were used. For questions related to LCA ($n = 34$), a 5-point Likert scale was used, allowing for a neutral midpoint to capture more nuanced or indifferent opinions [41]. In contrast, questions specific to BIM-LCA, answered by a smaller subgroup of 18 participants, contained a 4-point Likert scale, deliberately excluding a neutral option to encourage respondents to take a position, minimise central tendency bias and clarify group trends [42, 43].

The survey was divided into five parts:

(1) **Background and Professional Experience** – to characterise respondents by role, sector, and years of experience.
(2) **BIM Use and Maturity** – to assess BIM adoption and use.
(3) **LCA and Sustainability Practices** – to assess adoption and use of LCA, circular economy, and other environmental indicators.
(4) **BIM-LCA Integration** – targeted only at participants with BIM-LCA experience, focusing on its adoption, software use, perceived limitations and valued features.
(5) **Decision-Making Support** – to explore how professionals weigh environmental, economic, and social factors in design decisions, and how BIM-LCA is perceived to support that process.

A simplified visual overview of the survey structure and branching logic is provided in Fig. 2. The detailed of the survey flow is available in Appendix A, as well as all the questions and participants' responses.

2.1.3. Data treatment and analysis

Survey data were exported from Microsoft Forms and screened in Excel. Incomplete responses were excluded, retaining only fully completed questionnaires ($n = 62$). Data were analysed using Excel and Python. Descriptive statistics (frequencies, means, medians) were used to assess patterns across user profiles (e.g., 'BIM users, no LCA', 'LCA users, no BIM', and 'BIM-LCA users').

Given the ordinal nature and the relatively small sample size, non-parametric statistical tests were applied to analyse Likert-scale questions [44]. The Mann–Whitney U test was used to compare distributions between user profiles, while Spearman's ρ assessed monotonic associations between key perceived barriers of LCA adoption. For questions related to BIM-LCA barriers and valued features—answered by a smaller subgroup of respondents using a 4-point Likert scale—a Chi-square goodness-of-fit test was applied to evaluate whether the responses deviated from a uniform distribution.

The Technology Acceptance Model (TAM) [45] supported the

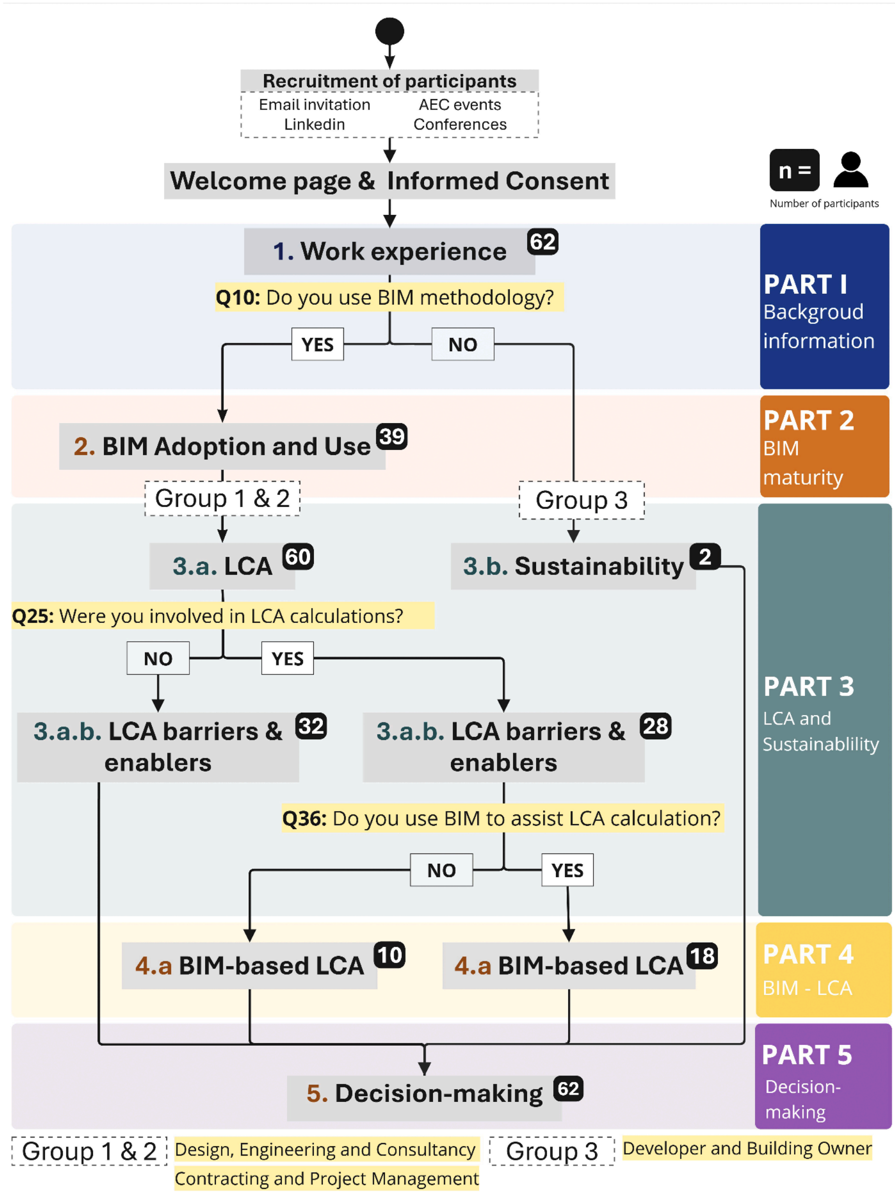

Fig. 2. Simplified structure of the survey. Depending on the responses, participants follow different branches. The numbers in the black boxes represent the number of participants who went through that particular branch. The detailed survey flow is provided in Appendix A.

qualitative interpretation of results, structured around: (1) *Perceived Usefulness* — whether BIM-LCA tools are seen as supporting decision-making and improving building performance; (2) *Perceived Ease of Use* — user perceptions of usability, degree of automation, and the need for manual data handling; (3) *Behavioural Intention / Actual Use* — reflected in frequency of use, application contexts, and willingness to adopt or recommend such tools.

It is important to acknowledge that the survey sample was limited in size and composition. While the insights generated are valuable for highlighting current tendencies and user challenges, the study is exploratory in nature and not statistically representative. Limitations related to sample size, potential bias, and participant distribution are critically discussed in Section 5.

2.2. Focus Group

2.2.1. Participant recruitment

Participants were recruited through purposive sampling, targeting professionals with proven experience in Building LCA. Eligibility criteria included documented involvement in at least one LCA project and demonstrable familiarity with BIM-LCA workflows or GBC schemes, which were verified through public profiles (e.g., LinkedIn, institutional bios).

Participants were contacted via email, informed about the session's purpose, data handling procedures, and voluntary nature, and provided informed consent in accordance with institutional ethical guidelines.

2.2.2. Data collection and analysis

The focus group was held online via Microsoft Teams and conducted in English to accommodate participants from different European countries (Portugal, Denmark, Bulgaria, Italy and United Kingdom). The session lasted approximately 90 minutes. A digital whiteboard (Miro platform) was used to guide the conversation visually and foster interactive contributions throughout the discussion.

The session followed a script composed of 11 open-ended questions, grouped into four thematic blocks: (1) LCA practices and experience; (2) Enablers and barriers to LCA; (3) BIM-LCA integration challenges; and (4) Decision-making criteria and trade-offs. Table 2 outlines the guiding

Table 2
Focus group question guide.

Topic	Questions	Time
Opening Questions	**1.** Are you familiar with LCA? If so, how would you describe it in your own words?	5 min
	2. Have you ever performed a building LCA? If yes, for what purpose?	5 min
	3. In which types of projects have you conducted an LCA?	5 min
LCA enablers and barriers	**4.** What are the enablers of using LCA?	10 min
	5. What barriers do you encounter when conducting an LCA? In your opinion, how could these challenges be overcome in the future?	15 min
BIM-LCA	**6.** Have you used BIM to support LCA? What benefits do you see in this approach?	15 min
	7. Which LCA software(s) have you used or are currently using?	10 min
	8. From your perspective, what is the current level of integration between BIM software and LCA tools?	
	9. What are the technical difficulties of conducting LCA with BIM? How can they be overcome in the future?	10 min
Decision-making	**10.** How do you evaluate trade-offs between environmental, economic and other factors?	10 min
	11. Which criteria do you use for each factor?	

questions used. This format fostered spontaneous discussion and interactive reflection, promoting deeper insights than one-to-one interviews, and is particularly valuable in small-samples and exploratory studies [46].

The session was recorded (with consent), transcribed, and manually analysed to identify key themes, which were then discussed with survey findings.

3. Results

This section presents the findings from the online survey with 62 professionals and the focus group with six experienced LCA practitioners.

3.1. Survey

3.1.1. Characterisation of participants

The survey collected valid responses from 62 professionals with varied experience levels, organisational and geographic contexts (Fig. 3). Most respondents were based in Portugal (n = 38), followed by the UK (n = 5), Spain (n = 4), Germany (n = 3), and others across Sweden, Belgium, France, and other European countries.

Participants had varied professional experience: 13% over 20 years, 23% 11–20 years, 39% 5–10 years, and 25% less than 5 years. Regarding the scope of their organisations, over half (56.5%) worked in internationally active firms, 37.1% in national companies, and 6.5% in firms with a local/regional reach. This suggests that although the majority of participants were based in Portugal, their insights reflect transnational AEC practices.

Most respondents (93.5%, n = 58) belonged to the Design, Engineering and Consultancy group. The remaining 6.5% were divided between the Contractor and Project Managers group (3.2%, n = 2) and the Developers and Building Owners group (3.2%, n = 2).

Within the Design, Engineering and Consultancy group, a substantial share was engaged in sustainability and environmental consulting (41.4%), academic research (29.3%), BIM modelling (29.3%), and project management (22.4%) (Fig. 4).

In Fig. 5 participants were categorised based on BIM and LCA adoption. The most common profile was "Users of BIM, no LCA" (33.9%, n = 21), followed by "Users of BIM-LCA" (29.0%, n = 18), "No LCA, no BIM Users" (21.0%, n = 13), and "Users of LCA, no BIM" (12.9%, n = 8). A smaller share (3.2%, n = 2) reported using both without integration. It is important to highlight that two inconsistencies were identified where respondents reported using BIM-LCA without reporting the use of BIM. For consistency, these two cases were excluded from the BIM-related questions in Section 3.1.2, which therefore accounted for 39 participants.

3.1.2. BIM maturity

Among all participants, 65% (n = 39) reported using BIM in their professional activity. BIM adoption was exclusively observed in the Design, Engineering and Consultancy group (n = 37) and among Contracting and Project Management (n = 2). None of the developers or building owners reported using BIM.

Participants had varying levels of BIM maturity, as defined by ISO 19650-1 [47]. The majority (46.2%) operate at Stage 1 - information is predominantly managed through the production of isolated models and documents, with limited coordination and no integration between disciplines. This was followed by Stage 2 (38.5%), where collaborative working is achieved using federated 3D models, often supplemented with 4D (time) and 5D (cost) dimensions, although file exchanges between stakeholders still occur. Only 15.3% reach Stage 3, where information is managed within Common Data Environments (CDEs) and distributed databases, enabling real-time, role-based data contributions without file-based exchanges (Fig. 6).

In terms of BIM uses, the most frequently cited applications were Design and Visualization (74.4%), Quantity Take-Off (58.9%), and Sustainability Analysis (56.4%), Clash detection (41.0%), Data Management (35.8%), and Cost Estimation (33.3%). Most participants reported multiple BIM uses; only four reported using BIM only as a design and visualization tool (Fig. 6).

Autodesk Revit was the most used tool (87.2%), followed by IFC (43.6%), ArchiCAD (25.6%), Dalux (12.8%) and Tekla Structures (10.3%). Moreover, most participants use more than one BIM software in their daily practice (Fig. 7). While predefined options were provided for BIM software, participants expanded their responses to include not only BIM authoring tools, but also data exchange formats (e.g., IFC) and common CDEs.

Regarding the use of CDEs, Autodesk Construction Cloud / BIM 360 was the most mentioned, used by 61.5% of participants. However, a notable proportion (30.8%) reported not using any construction-specific CDE.

The IFC format was also identified as the preferred method for BIM data exchange, adopted by over 80% of participants.

These findings suggest that while BIM is widely used by participants, maturity levels vary considerably, and full digital collaboration is not yet common practice.

3.1.3. Building LCA and Sustainability Practices

A total of 51 respondents reported implementing sustainable building practices in their projects (85% of valid responses in this group, n=60; or 82.2% of the full sample, n=62) (Fig. 8). The most common strategy was the integration of renewable energy systems (58.3%), such as photovoltaic panels and solar thermal collectors—often required by national regulations (e.g., in Portugal, Decree-Law no. 101-D/2020 mandates solar-based domestic hot water in new buildings and major renovations). Other frequently adopted strategies include passive design (56.6%); Design for adaptability (53.3%); and the use of low-carbon materials (48.3%), including timber, recycled aggregates, and geopolymer binders.

In terms of familiarity with Circular Economy (CE) strategies, 20% reported regular use, 15% had applied CE once, 16.7% had basic knowledge,43.3% could understand the CE principles and identify their benefits, and 5% did not know what these were.

Regarding GBCs, 39 participants had worked on certified projects (62% of the full sample, n = 62; 65% of the valid responses in this goup, n = 60). The most common systems were BREEAM (n = 25, 41.6%) and LEED (n = 24, 40%), followed by Level(s) (n = 14, 23.3%), WELL (n = 6,

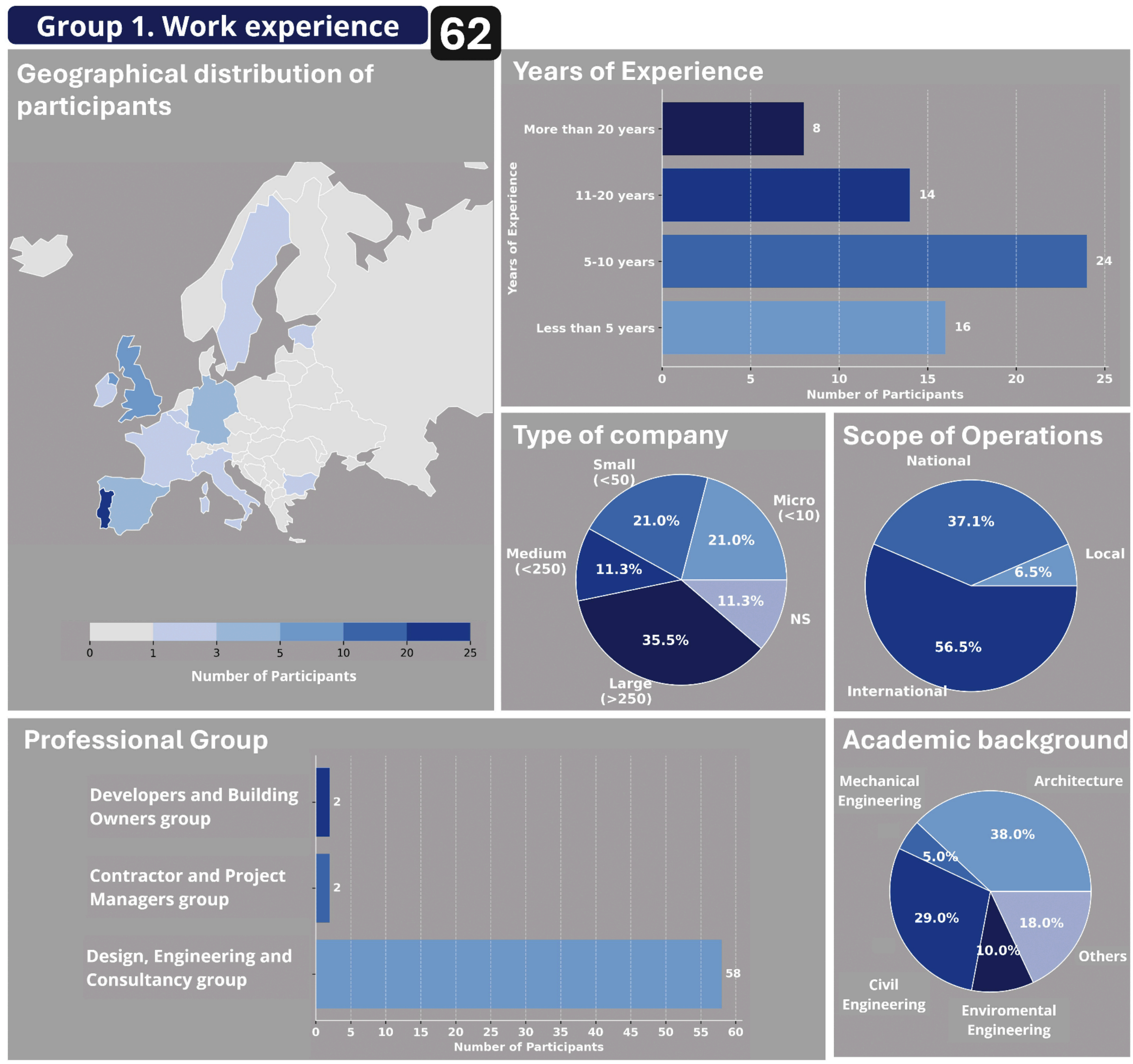

Fig. 3. Levels of experience, organisational contexts and geographical distributions of participants (n= 62).

10%), and DGNB (n = 3, 5%). A few respondents also reported using national or niche schemes, such as EDGE, LiderA, SBTool, HQE, HPI, NollCO2, and Miljöbyggnad (Fig. 9).

Regarding LCA experience, 17 participants (28.3%) had heard of LCA but had no practical experience, while 16 participants (26.6%) were familiar with the method and capable of interpreting results, and 14 participants (23.3%) self-assessed as LCA experts (Fig. 10). The remaining 12 participants (19.3%) had performed at least one LCA, and one participant reported not knowing what LCA was.

When asked whether any of their projects had been subject to LCA, 37 participants (61.6%) answered affirmatively, with only 28 directly involved in the LCA calculations, representing 45% of the full sample (n = 62) or 46.6% of the valid responses in this group (n = 60). In comparison, only 33 participants (53.0%) confirmed their projects underwent a Life Cycle Cost Analysis (LCCA), suggesting that LCCA is used less frequently than LCA. A similar trend was observed in a study conducted in New Zealand [48], which also found that LCCA is typically applied less often than LCA (Fig. 10).

In summary, most participants reported implementing sustainable design strategies (85%) and working with GBCs (65%) but the use of LCA remains limited (46.6%).

3.1.4. Building LCA use

This sub-section analyses responses from participants with LCA experience (n = 28).

More than of respondents (n = 16; 57.1%) reported conducting LCA on most projects, and five (17.9%) on every project (Fig. 11). LCA is most often conducted during the Detailed Design phase (n = 15; 53.5%), when key decisions have already been made—indicating limited use in early design and continuous monitoring throughout the design process.

The main motivation for LCA is compliance with GBCs (n = 20, >70%), followed by supporting design choices (n = 11, 39.2%) and meeting regulatory requirements (n = 7, 25%). Overall, LCA is still perceived primarily as a compliance tool, rather than as a decision-support instrument for comparing design alternatives (Fig. 11).

Nine participants (32%) had used LCA in new construction, two (7%) in renovations, and 17 (61%) in both. The most frequent building typologies assessed were commercial (68%), multi-residential (60%), and single-residential (42%) (Fig. 12).

LCA studies typically included substructure, superstructure, envelope, and finishes. Other components—such as services, fit-out, and external works—were cited less often, likely due to their optional inclusion in GBC requirements.

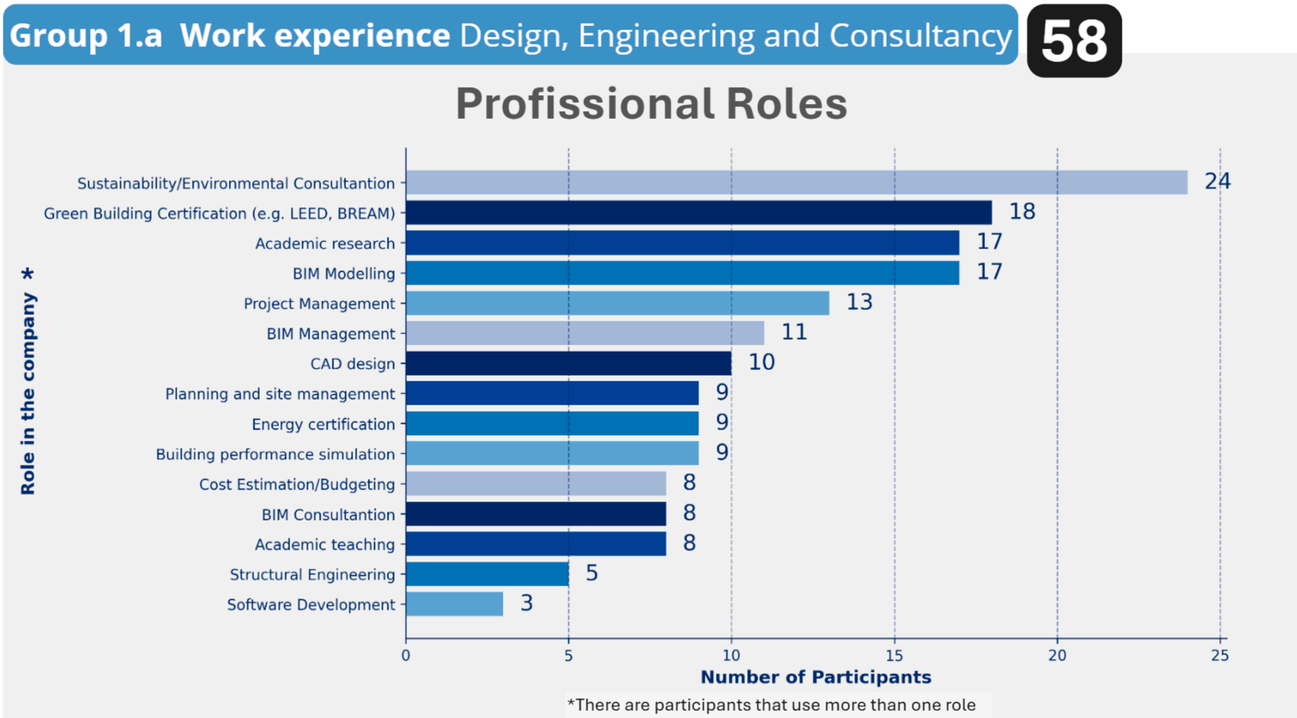

Fig. 4. Professional roles of participants within the design engineering and consultancy group (n=58).

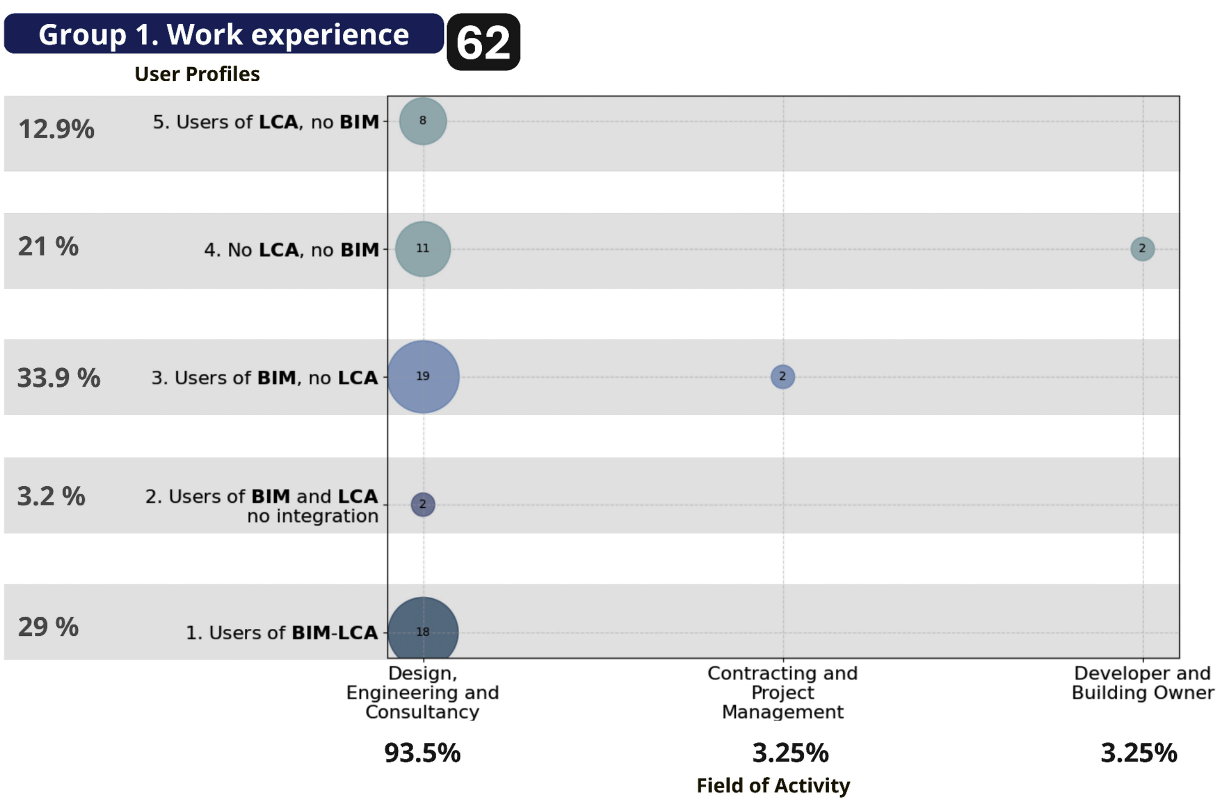

Fig. 5. BIM and LCA user profiles versus field of activity of participants (n = 62).

Regarding lifecycle scope, most participants (46.4%) adopted a cradle-to-cradle approach, and a 21.4% cradle-to-grave (Fig. 13). Furthermore, most respondents (63.3%) assessed multiple impact categories, 21.4% used all indicators defined by the LCIA method, and 14.3% focused exclusively on GWP (Fig. 13).

The most common LCIA method was the Environmental Footprint (EF 3.0), followed by the CML method. Several practitioners reported using both when dealing with GWP [49]. Practitioners often still rely on

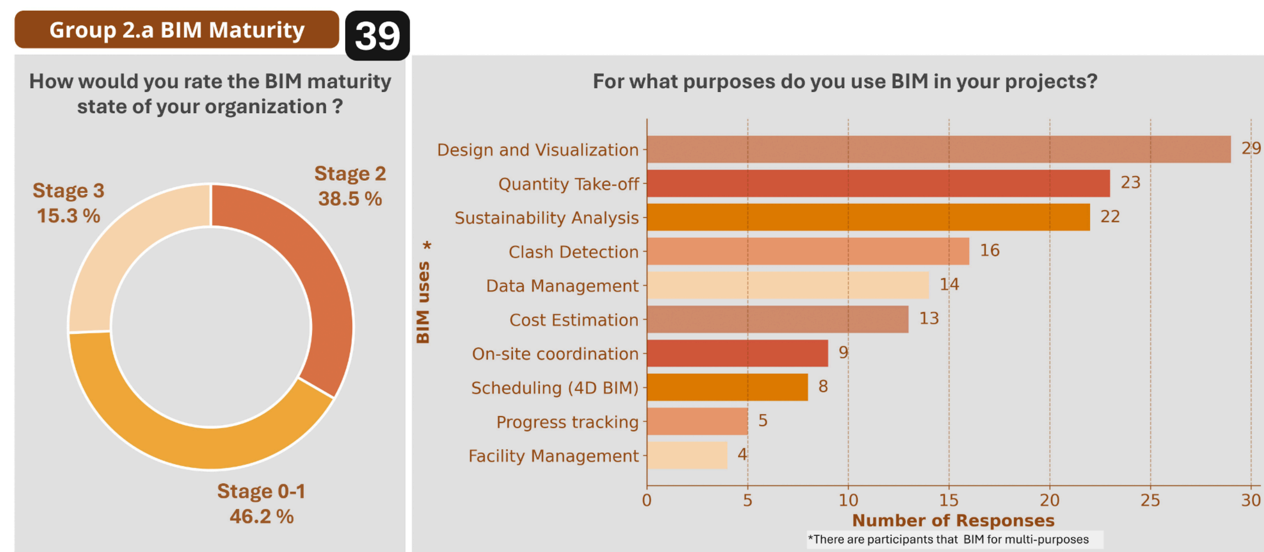

Fig. 6. BIM maturity of the participants who reported using BIM in their professional activity (n=39).

CML-based GWP values when using older EPDs aligned with EN 15804+A1 (2013), whereas others adopt EF 3.0 following updates introduced in EN 15804+A2 (2019) [12].

Some participants cited ISO 14040 or LCA databases instead of LCIA methods, suggesting methodological confusion among less experienced professionals or practitioners without solid theoretical background. This highlights the need for transparency and clear communication of assumptions by LCA tools. Clearly defining the LCIA method is essential to ensure consistency, interpretability, and traceability of results (Fig. 13).

3.1.5. Barriers to LCA adoption

Participants evaluated potential barriers to Building LCA adoption using a 5-point Likert scale (1 = not a barrier; 5 = extreme barrier). The most frequently reported barriers were: (1) lack of representative LCA data on construction materials (mean = 3.5), (2) absence of national Environmental Product Declarations (EPDs) (mean = 3.4), (3) lack of client demand (mean = 3.38), (4) manual processes involved (mean = 3.34), and (5) time and cost to perform an LCA (mean = 3.3) (Fig. 14).

A Mann–Whitney U test was conducted between two groups: LCA users (n = 28) and Non-users (n = 32) to examine how practical experience with LCA influences perceptions. No statistically significant differences were found between the two groups ($p > 0.05$ in all cases), suggesting that, barriers are perceived similarly regardless of practical experience. Although distinct trends are already apparent, obstacles such as lack of representative LCA data and local EPDs, manual processes involved, and time and cost to perform a LCA are considered more relevant by users. On the other hand, *lack of demand from clients* is perceived as more relevant by non-users. I do not understand, or I do not know responses are more common among non-users, occurring up to four times per barrier.

Table B1- Appendix B provides the full list of identified barriers, including mean values, medians, user group comparisons, and Mann–Whitney U test results.

A Spearman's rho correlation analysis was also conducted to explore relationships between barriers (detailed results in Table B2 - Appendix B).

The strongest correlation was between the lack of EPDs and the lack representative LCA data correlation ($\rho = 0.86$). Participants correctly recognised that EPDs offer product-specific environmental data, making them significantly more accurate than generic datasets—differences between the two can exceed ±50% for all impact categories [50]. However, such databases are scarce. For instance, in Portugal, where most participants are located, there are currently only 67 EPDs available for local construction materials and products [51].

A moderate correlation was found between the absence of national EPDs and the lack of governmental incentives for performing *LCAs* ($\rho = 0.57$). Policy instruments are seen as drivers of EPD development by encouraging manufacturers through regulatory and market pressures. Similarly, the absence of government incentives was strongly linked to low client demand ($\rho = 0.53$), emphasising the importance of top-down policies in shaping market expectations and public policy.

Additionally, the manual processes were moderately correlated with complexity of an LCA ($\rho = 0.50$), linking technical effort to perceived difficulty.

3.1.6. Adoption of BIM-LCA

Of the 28 participants with LCA experience, 18 reported using BIM to support LCA (Fig. 15). Among the 10 non-users, most rated BIM's potential to improve LCA workflows as slight or moderate, while only three (10.7%) saw significant benefits. This distribution suggests that, while there is general optimism regarding BIM-LCA integration, confidence in its current implementation remains limited. Non-users identified the LCA processes most likely to benefit from BIM as: collecting inventory (80%), mapping LCA data to elements (70%), and fast comparison of design options (60%).

Among the 18 BIM-LCA users, the majority rated current integration levels between 1 and 3 on a 4-point scale, indicating current BIM-LCA depend on manual or semi-automated workflows (Fig. 15). Common BIM-LCA tools included OneClick LCA and Autodesk Tally, along with Excel exports, BIM add-ons, and custom solutions (Fig. 16).

The level of development (LOD) of the BIM objects in varied, with LOD 300 being the most frequent, which is consistent with the fact that LCA is typically carried out after detailed design (Fig. 16). Although the term LOD has been replaced by Level of Information Needed (LOIN) in ISO 19650-1 [47] and ISO 7817-1 [52], the former was intentionally used in the survey to simplify communication. LOIN, unlike LOD, does not rely on scalar levels, making it harder to use in questionnaire design, and might be less familiar to participants.

Only 10 participants (55.6%) stated that their BIM-LCA tools support continuous assessment of environmental impacts throughout the design phases.

Most participants (77.7%) reported importing the BoQ into LCA tools using standard formats (e.g., CSV, XLSX, IFC), but 64.2% stated that manual editing was still required. The most frequently edited elements

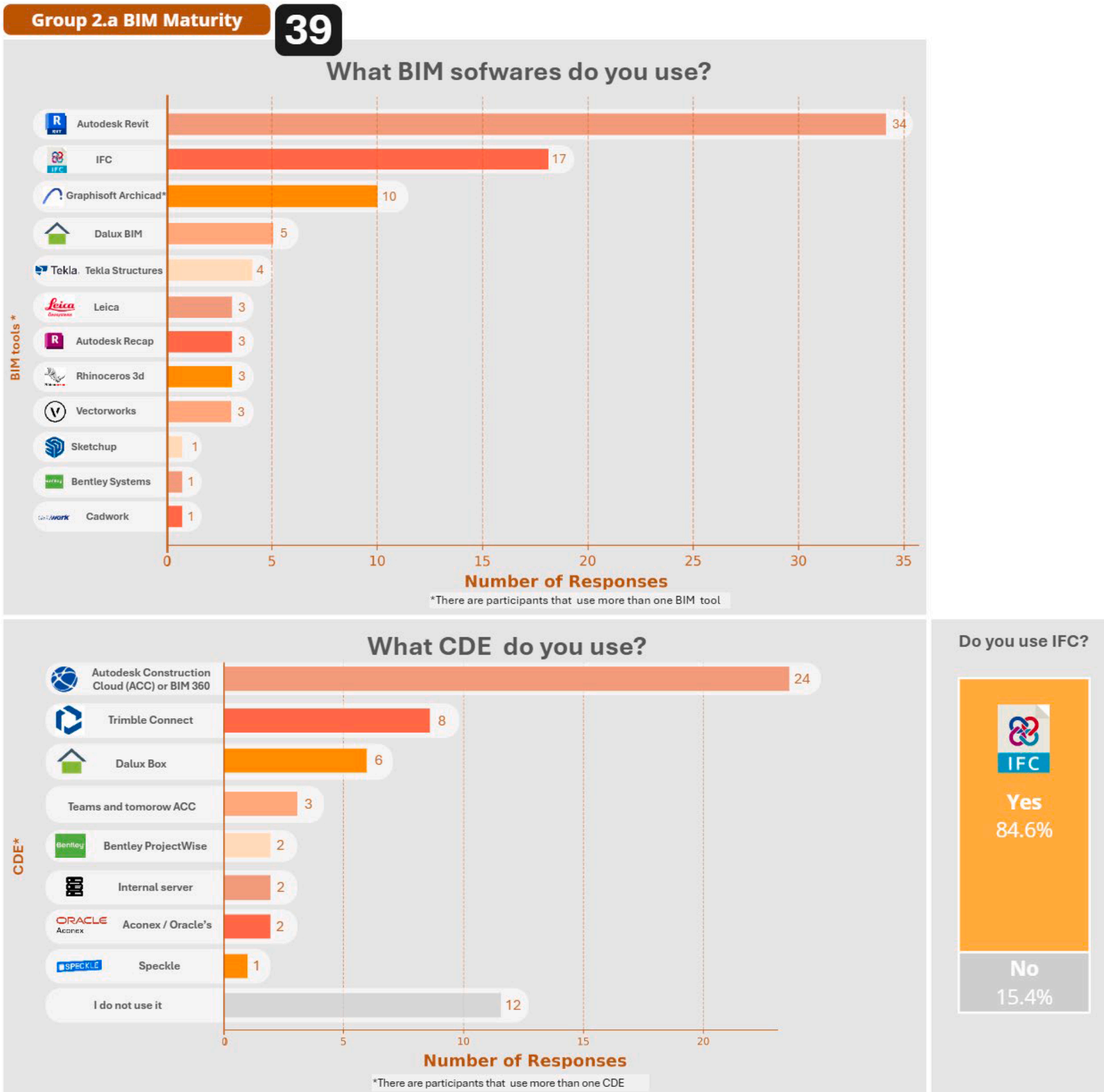

Fig. 7. Reported BIM software and CDE (n=39). Participants expanded their responses to include not only BIM authoring tools, but also data exchange formats, and CDEs.

were walls and floors, followed by roofs, stairs, windows, and railings. Less frequent but also mentioned were columns, doors, and duct fittings (Fig. 17).

Regarding mapping between BoQ and LCA data, 27.8% used fully manual processes, 22.2% relied on software-saved user preferences (e.g., OneClick LCA), and others used predefined Excel sheets (16.7%), BIM templates (16.7%), or natural language processing (16.7%). No respondent reported using a Construction Classification System (CCS) (Fig. 18).

When asked about the capacity of their BIM-LCA tools to support the comparison of design options, most users stated they could compare material alternatives by editing the BIM model and re-importing the BoQ into LCA software. A strong consensus emerged around the need for parametric design and real time feedback, with 17 participants (94.4%) agreeing that it would be beneficial to have access to a catalogue of predefined building solutions (e.g., walls, roofs, windows, structures) that can be simulated rapidly without remodelling, especially in early design (Fig. 18).

Participants reported that some of the BIM-LCA platforms also support additional types of analysis beyond environmental assessment. These included LCCA and Circularity Score (Fig. 19). Regarding EPD access, 55.6% found them accessible (i.e., easy to locate and download in usable formats), while 44.4% cited issues related to format, language, compatibility with BIM-LCA tools. Similarly, 61.1% reported being able to add new EPDs or generic data to BIM-LCA software, while others lacked that functionality or were unsure.

3.1.7. Perceived Limitations and Prioritised Features of BIM-LCA Tools

BIM-LCA users were asked to assess the perceived limitations of BIM-LCA tools using a 4-point Likert scale (1 = Not a limitation; 4 = Major

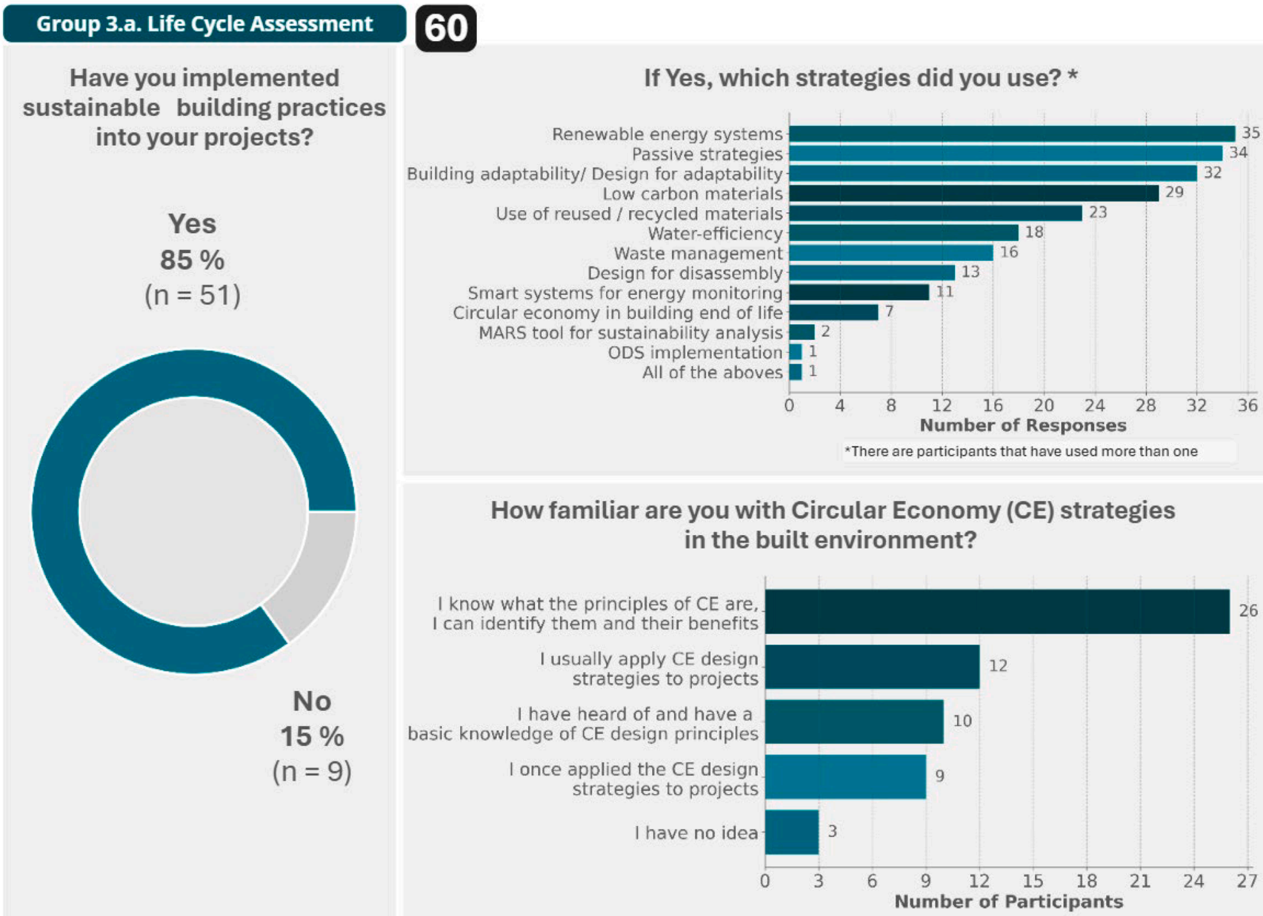

Fig. 8. Sustainable building practices of the participants (n = 60).

limitation). A 4-point scale was used to eliminate neutrality and reduce central tendency bias. A Chi-square goodness-of-fit test determined whether response distributions were random ($p < 0.05$ considered significant). Measures of central tendency (mean, median, mode) were also calculated.

The most significant perceived limitation was the lack of representative LCA data (mean = 3.06), with a statistically significant result ($p = 0.0123$). Manual mapping between BoQ and LCA data also scored high, but did not reach statistical significance ($p = 0.0919$), indicating a slightly more variable perception among participants. Other commonly cited issues included: poor integration between BIM and LCA software, manual editing of BoQ, lack of support for early design, high modelling effort, and demanding information requirements. Complete statistical results are provided in Table B3 (Appendix B).

Participants also evaluated the importance of different features in BIM-LCA tools, using a 4-point Likert scale (1 = Not important; 4 = Very important). The most valued was access to a comprehensive LCA database (mean = 3.50, $p = 0.0007$), followed by automatic BoQ/LCA mapping (mean = 3.44, $p = 0.0004$). Other prioritised functionalities included compliance with GBCs, real-time synchronisation with the BIM model, and simplified comparison of design alternatives. All showed statistically significant distributions, indicating broad consensus (Table B4- Appendix B and Fig. 20).

An optional open-ended question was included to explore the main obstacles to using BIM-based LCA tools. Several common themes and concerns emerged. The complete responses are in Table B5 - Appendix B. One of the most frequently cited issues was the poor quality of BIM modelling, with participants referring to "mistakes and modelling that deviate from industry standards" and "poor modelling in BIM software." These reported issues indicate that the information requirements necessary for effective BIM-LCA integration are not being met—either due to inadequate definition of these requirements or their omission from the BIM Execution Plan (BEP), often worsened by limited coordination between design and sustainability teams. These gaps undermine automation and reduce the reliability of LCA results.

Participants also highlighted a lack of experienced professionals and limited education or training in the combined use of BIM and LCA. Additionally, the high cost of BIM-LCA tools and their poor alignment with typical architectural and design workflows were identified as barriers, suggesting that these tools are not yet fully embedded in design practice.

3.1.8. Decision-making methods

Among the 62 respondents, most agreed on the importance of balancing environmental, economic, and social factors (43.6% “Very important”; 32.2% “Moderately important”). The most frequently used criteria are material and construction costs (46.7%) and long-term operational and maintenance costs (37%) followed by embodied carbon 30.6%) and operational energy (29%), as shown in Fig. 21.

Regarding decision-making methods, Multi-Criteria Decision Analysis (MCDA) approaches were the most reported (43.5%), followed by personal insight and experience (33.8%). A smaller proportion of respondents (14.5%) cited more advanced techniques, such as multi-objective optimisation. However, this unexpectedly high report of MCDA use may reflect a misinterpretation of the question. It is likely that some respondents associated MCDA with general prioritisation or balancing of criteria—such as cost versus carbon—rather than the application of formal methodologies such as Analytic Hierarchy Process

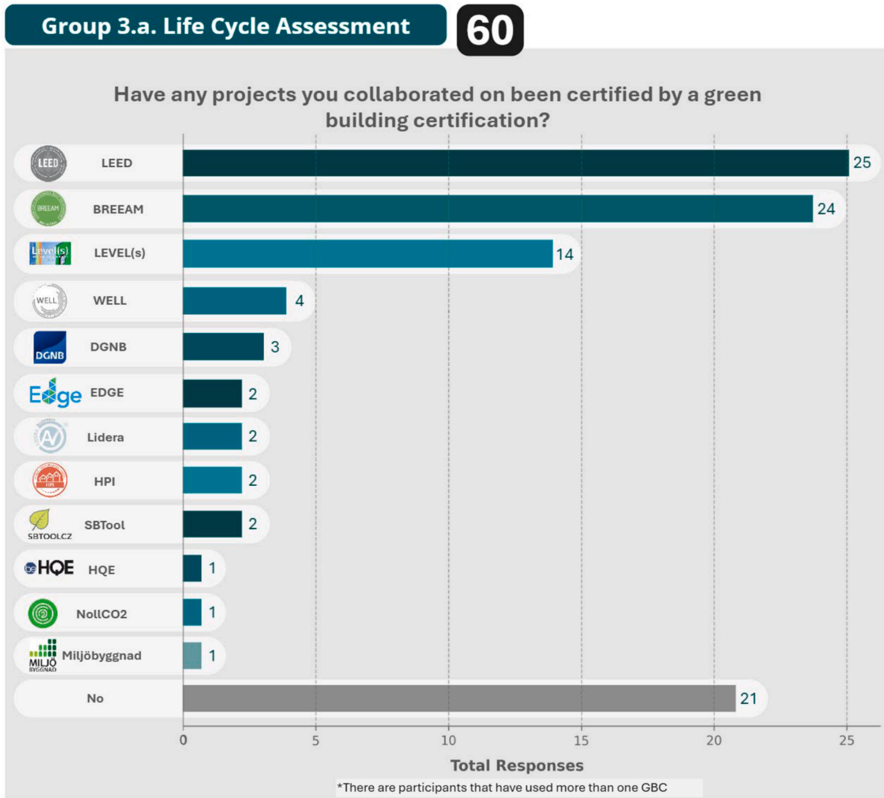

Fig. 9. GBCs used by participants (n = 60). Some participants cited more than one GBCs.

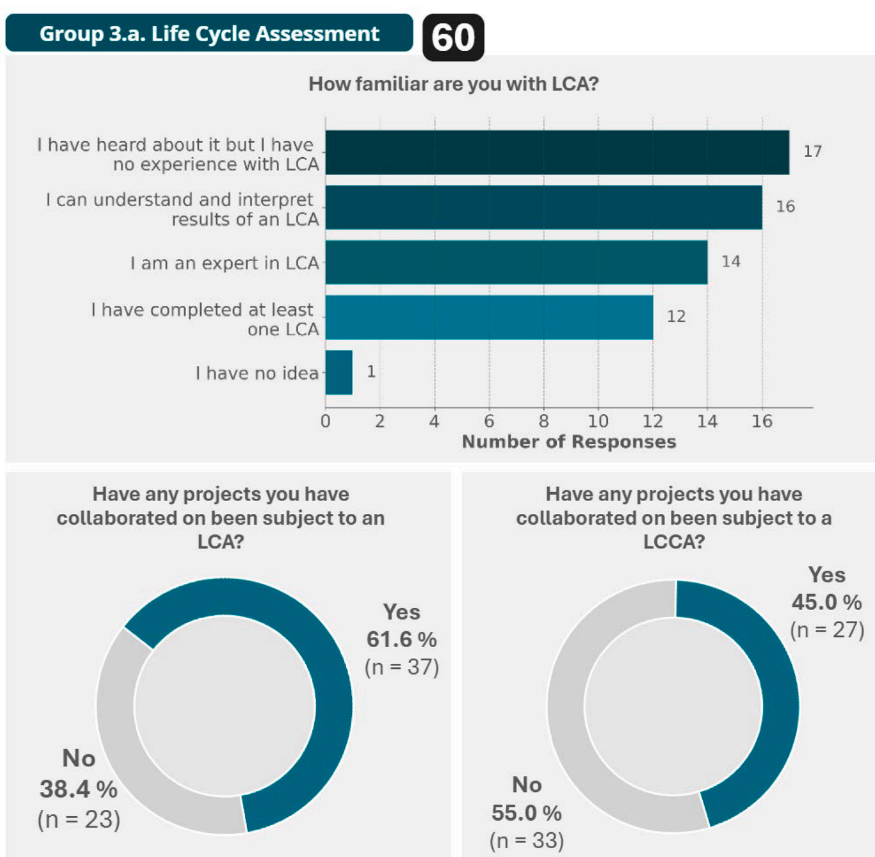

Fig. 10. Participant familiarity and collaboration in projects subject to LCA and LCCA.

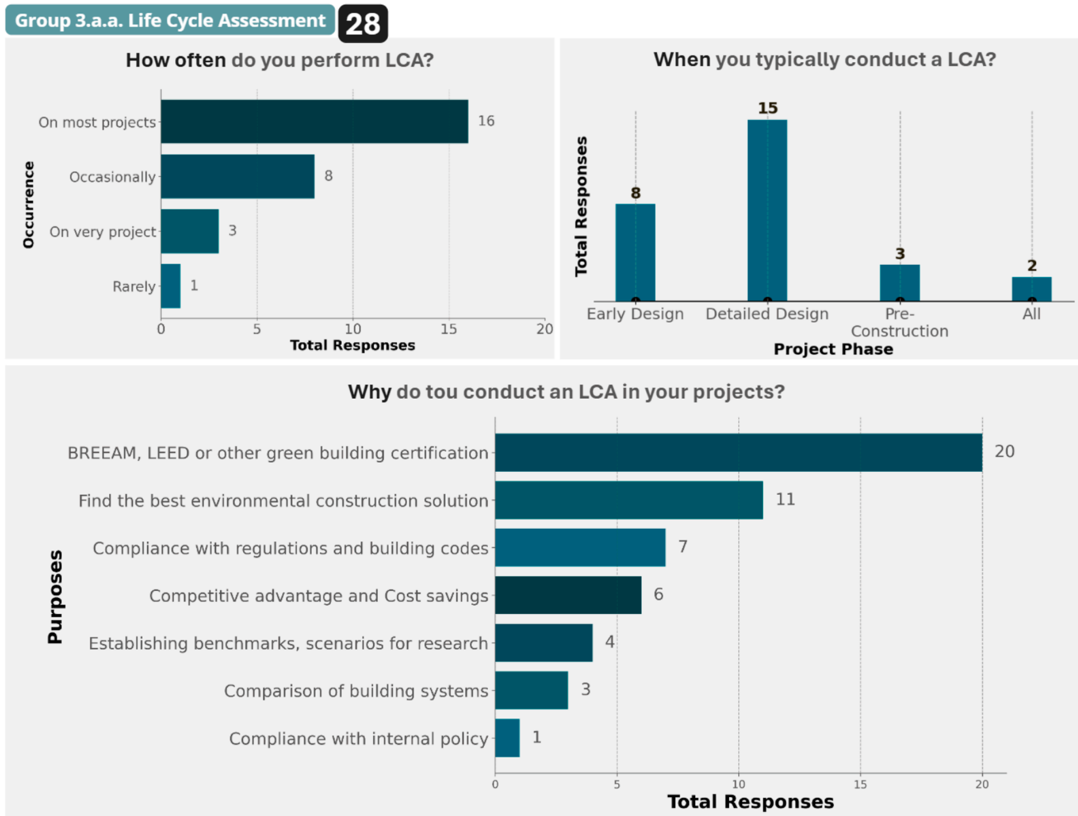

Fig. 11. How often, when and why participants (n=28) perform LCA.

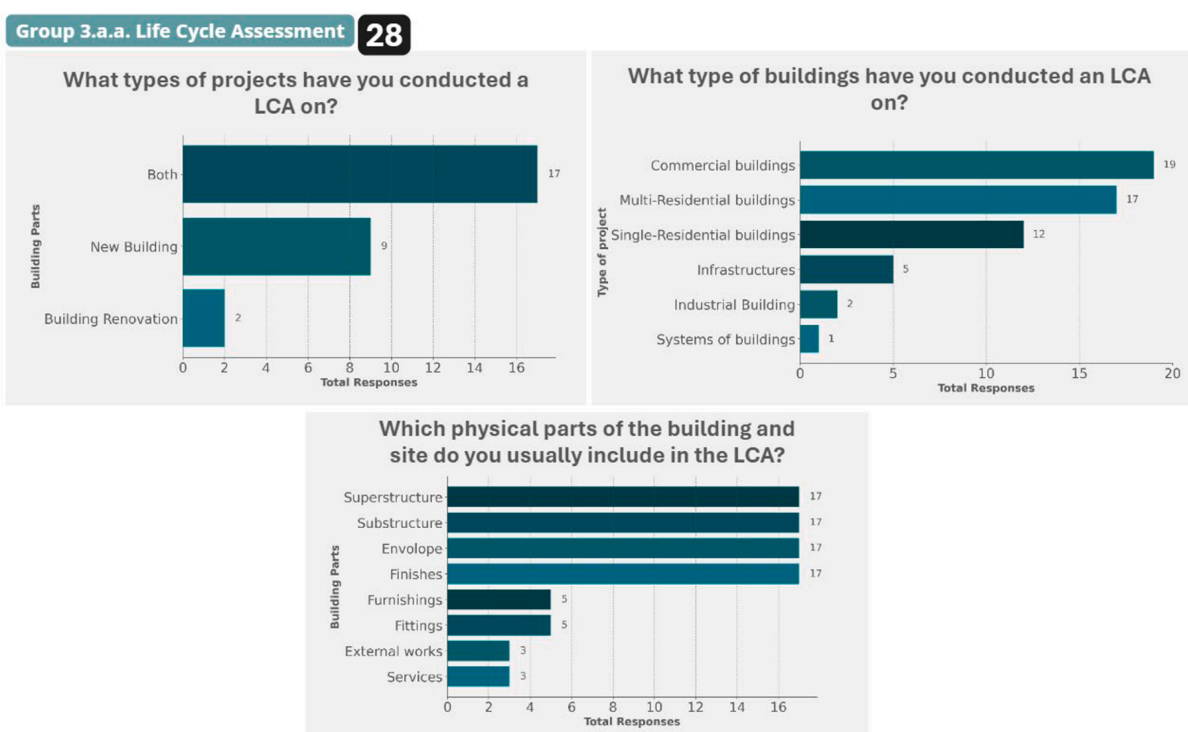

Fig. 12. The types of projects and building component are included in an LCA (n = 28).

(AHP) or Technique for Order Preference by Similarity to Ideal Solution (TOPSIS).

"Users of LCA with BIM" (Profile 1) reported the most systematic use of MCDM and weighted averages. This group, along with the Users of LCA, no BIM (Profile 5), was the most likely to rely on quantitative indicators, such as embodied carbon, operational energy, and construction

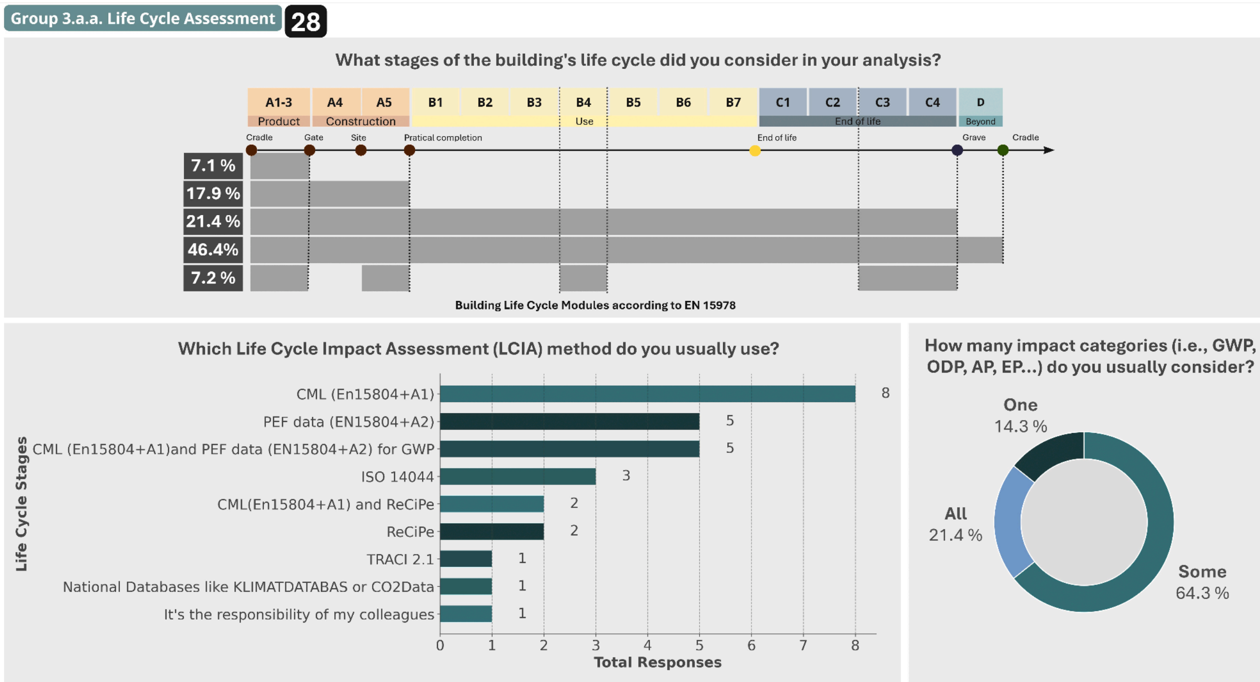

Fig. 13. Building lifecycle stages according to EN 19978, impact categories, and LCIA methods used by LCA participants with experience (n = 28).

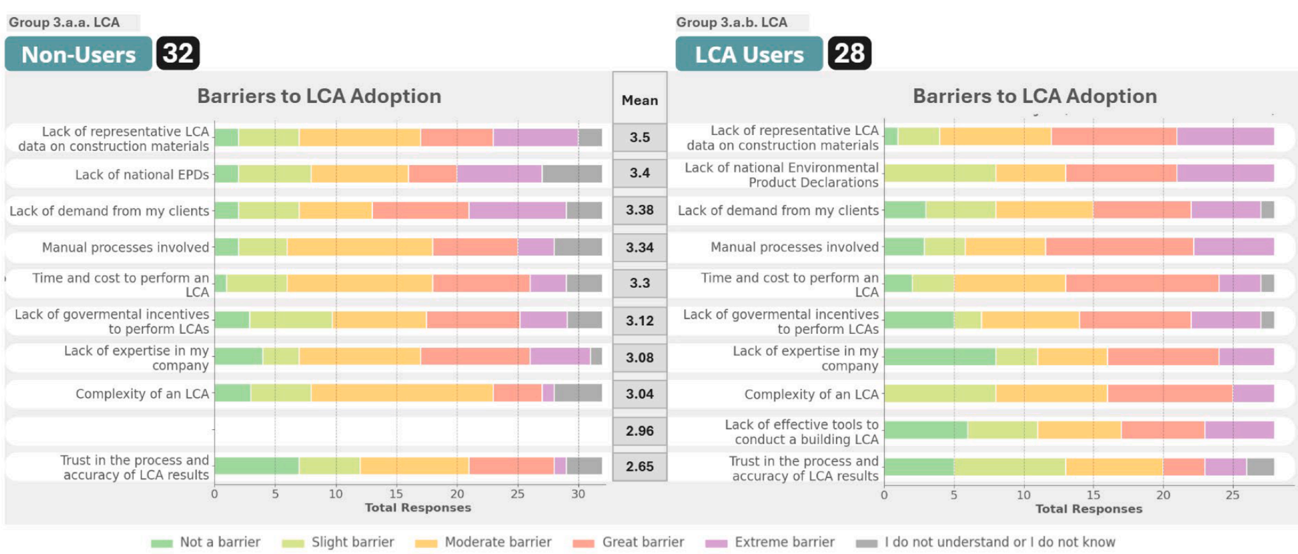

Fig. 14. Perceived barriers to LCA among non-users versus users.

costs, when making decisions.

In contrast, professionals in the "BIM and LCA no relation" (Profile 2) and "Users of BIM, no LCA" (Profile 3) profiles primarily relied on intuition and professional experience, with decisions largely driven by cost and constructability, rather than environmental metrics. The "No BIM, no LCA" (Profile 4) group showed the lowest engagement in structured or analytical decision-making.

When asked whether integrating a decision-support module for trade-off analysis into LCA software would improve their design workflows, 83.4% of participants responded positively. However, several participants cautioned that such tools should support—rather than replace—expert judgement, which remains essential for interpreting results, accounting for project-specific constraints, and avoiding errors. This underscores the need for professionals to possess the necessary competencies to make informed, context-sensitive decisions when using decision-support systems.

3.2. Focus Group

3.2.1. Characterisation of participants

The focus group included six participants with diverse professional backgrounds (Table 3). All participants had prior experience applying LCA within the AEC sector, either in practice, research, or consultancy. The group was geographically diverse, comprising professionals based in Portugal, Denmark, Bulgaria, Italy, and the United Kingdom.

3.2.2. LCA adoption and use

Participants emphasised that building LCA differs significantly from

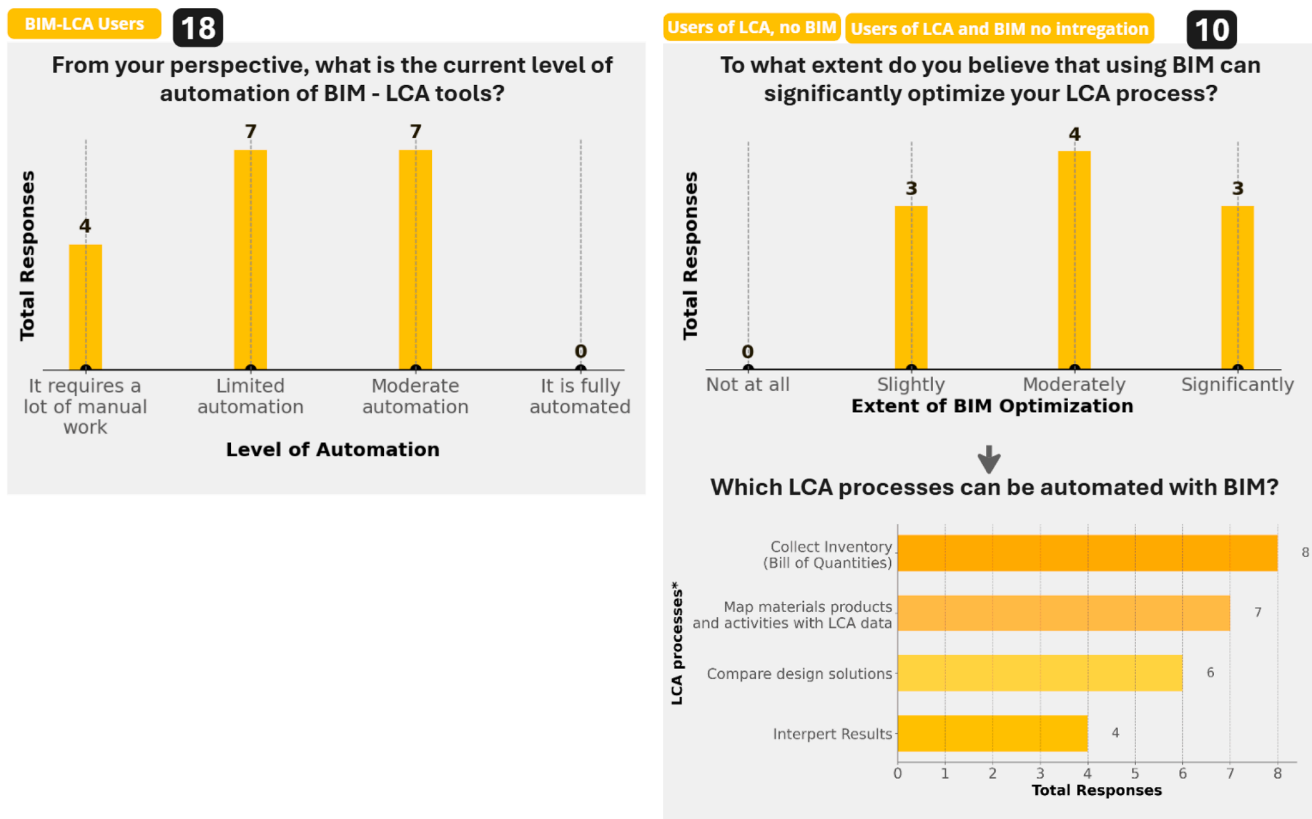

Fig. 15. Perceived level of automation that LCA can achieve through BIM integration (n =18).

product LCA due to its complexity, longer lifecycle, and site-specific characteristics.

A dominant theme was the compliance-driven nature of current LCA applications. Most participants referred to its use in response to certification schemes (e.g., BREEAM, LEED) or local carbon regulations, rather than as a voluntary or integrated design aid. For example, P5 (UK) explained: *"It's basically on request. Clients come to me because GLA (Greater London Authority) makes it mandatory."* On the other hand, P4 (Portugal) added: *"We've worked with several BREEAM certifications… LCA is often included, even if it is simplified."*

Another significant point was the contrast between practice and academia. LCA in academia is seen as a pedagogical and exploratory tool, supporting conceptual design thinking and sustainability literacy. As noted by P1 (Denmark), *"We use LCA to guide students in evaluating trade-offs… even if we don't have full data, it helps shape better design paths."*

The cost-benefit trade-off of full versus simplified LCA was also a recurring point. Participants indicated that although simplified LCA is faster, it yields fewer certification credits and is therefore unattractive unless required by clients. P5 (UK) cautioned that *"simplified LCA gives very few credits, so most clients prefer complete analysis if aiming for certification."*

Crucially, participants expressed concern that LCA is typically introduced too late to influence early-stage decisions. As P6 (Portugal) stated: *"LCA has potential to be generative in design, but too often it's just a box-ticking exercise near the end."* P4 (Italy) noted that *"LCA enables us to evaluate various design strategies and comprehend their long-term implications—even when not all data is available upfront"*.

In practice, however, this potential remains largely unrealised due to constraints related to time, budget, and client demand—when LCA is not explicitly requested or financed by the client, it is typically omitted from the design process.

3.2.3. *LCA of building renovation and retrofitting is challenging*

Participants had experience conducting LCA across various project types, including new construction and building renovation. However, due to data limitations and methodological uncertainties, renovation and retrofit projects were consistently described as more challenging. As P4 (Italy) noted, "In the case of renovation, we face more problems, specifically in terms of getting the information from the existing building".

A recurring concern was the difficulty in identifying the specific materials and systems present in the existing building, along with their current physical condition (material composition, degradation, or potential for reuse). Moreover, participants emphasised that even when materials are technically reusable, their effective reuse is often constrained by limited contractor knowledge and insufficient training in reuse-oriented construction techniques. These issues must often be weighed against project objectives, client priorities, and tight timelines, making the implementation of LCA in renovation contexts particularly complex.

3.2.4. *Enablers and Barriers to LCA adoption*

Participants were asked to discuss enablers that support the adoption of Building LCA. One strong factor was regulatory pressure, particularly at national and local levels (P5, UK). Several participants cited the revised Energy Performance of Buildings Directive (EPBD) as a significant upcoming driver. As P4 (Portugal) noted, *"From 2030, every new building will need to declare GWP. This is going to push everyone—designers, manufacturers, consultants"*.

GBC schemes were also highlighted as influential enablers, followed by market competitiveness and growing client demand. P3 (Italy) explained: *"Some clients now want numbers. Not just 'green' promises. They ask for LCA results to demonstrate the impact". P5 (UK) added "Clients seek green loans to reduce embodied carbon or to comply with BREEAM, LEED, or GLA requirements"*.

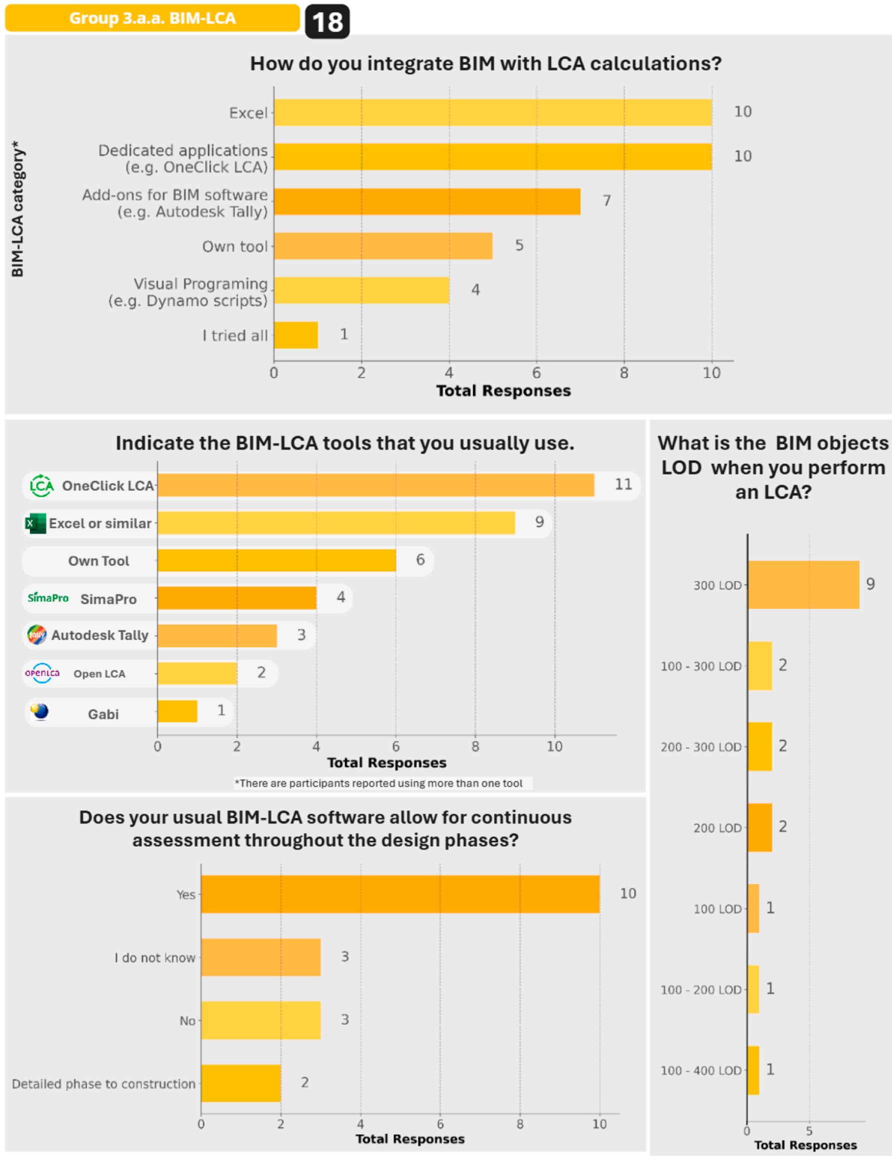

Fig. 16. Use of BIM-LCA tools, BIM objects' LOD, and whether BIM-LCA software enables continuous assessment throughout the design stages.

In the manufacturing sector, policy incentives and taxation were seen as strong drivers. P5 (Portugal) described how upcoming carbon taxation has accelerated the development of EPDs in the steel industry: "Starting in 2026, imported steel will be taxed based on its embodied carbon." That will push them to produce EPDs quickly". Carbon taxation mechanisms such as the Carbon Border Adjustment Mechanism (CBAM) and the revision of the Construction Products Regulation (CPR) will require manufacturers to disclose verified environmental data—particularly through third-party certified and machine-readable EPDs—which are essential to ensure data quality and availability for Building LCA.

All participants agreed that regulations, certifications, and market expectations are the key drivers of LCA adoption, though their impact depends on local context, client awareness, and supply chain maturity.

In terms of barriers, all participants agreed that the most cited issue was the lack of reliable, standardised, and transparent environmental data. P4 (Portugal) stated, *"We often use data without third-party verification". On the other hand,* P2 (Bulgaria) highlighted another important aspect: the lack of local EPD-based databases. "*Most of the available data here is generic… It's not specific to local producers, which skews the results."*

Participants also mentioned the need to establish building benchmarks. As P6 (Portugal) put it: *"We don't have clear benchmarks. For energy use, it's easier. But for LCA, we don't know what's good enough."* P5 (UK) further added that GBCs have varying requirements and practitioners use different system boundaries and LCIA methods. P5 (UK) referenced the Low Carbon Building Initiative (LCBI) [53] as a promising effort to harmonise LCA practice across Europe. Participants also recommended the creation of shared repositories of anonymised Building LCA results to support benchmarking and target-setting.

Modelling specific lifecycle phases—particularly A5 (construction), B1 (use), B3 (repair), and C1 (deconstruction)—was noted as particularly problematic. These stages often rely on assumptions, and there is currently no standardised method to report uncertainty. As P6 (Portugal) explained, "We're missing guidance on how to deal with these later phases… there's no established way to report LCA results with uncertainty ranges."

3.2.5. Perceived Limitations and Prioritised Features of BIM-LCA Tools

Participants agreed that BIM has strong potential to streamline Building LCA through automated quantity take-off (QTO) and its compatibility with parametric design. However, several limitations were reported, especially in the early stages of integration between BIM and

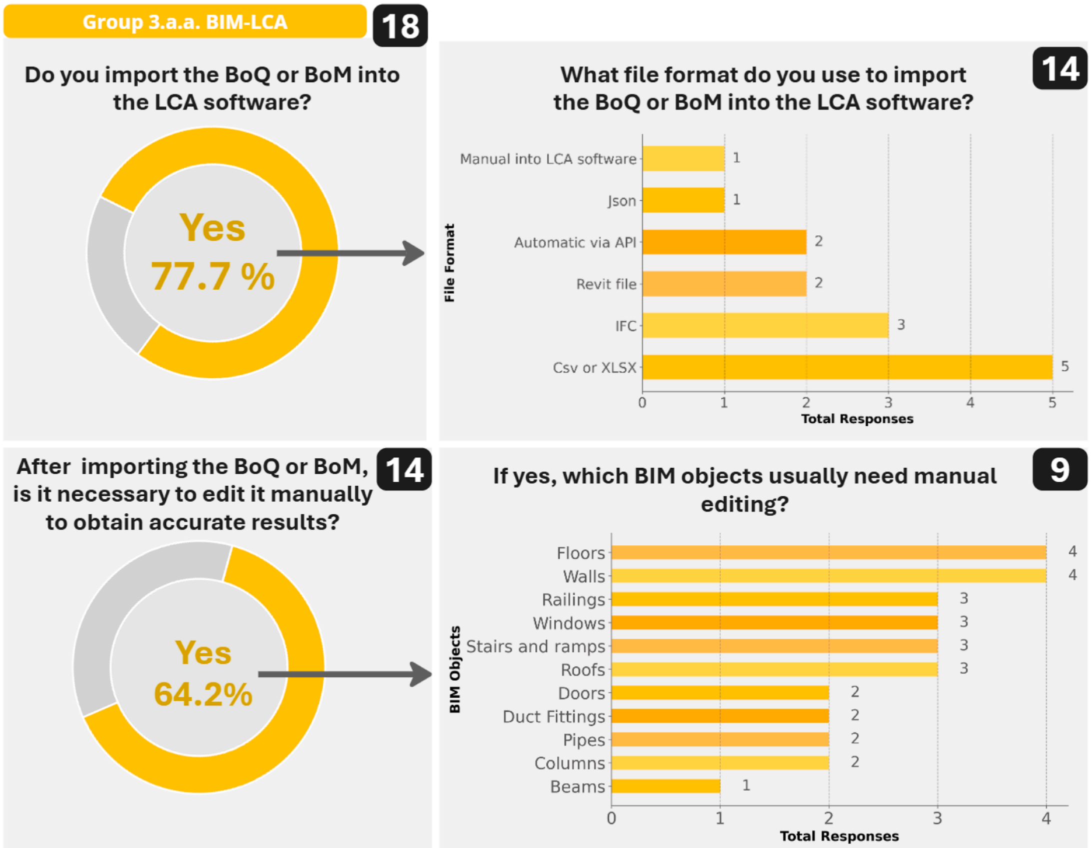

Fig. 17. Graphics illustrating if participants have to edit the BoQ, which file is used for data exchange and which BIM objects they normally edit.

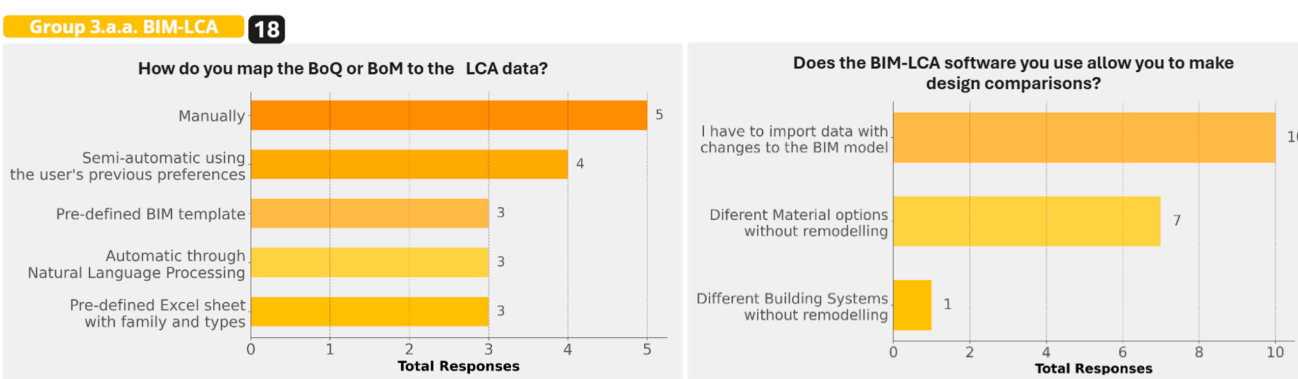

Fig. 18. BoQ to LCA data mapping, and design comparisons through BIM-LCA tools.

LCA. A recurring concern was the lack of clearly defined information requirements necessary for ensuring compatibility between BIM models and BIM-LCA tools.

The information requirements—such as classification codes, naming conventions, Level of Detail (LOD), object parameters (e.g., material specification, layer structure, thickness), and other metadata—should be clearly defined in the BEP, as they depend on the specific BIM-LCA tool employed. Without adherence to these specifications, automated data extraction and mapping is not feasible. As P5 (UK) noted, "*I have tried to use BIM, but since the professionals creating the model lacked knowledge of LCA, the tool was unable to read the model correctly. The time taken to correct was long.*" P4 (Italy) also described the extraction and alignment process as "tedious", due to the lack of structured outputs from IFC exports. Additionally, P1 (Bulgaria) raised concerns about the inconsistency and unreliability of BoQs generated from BIM models.

Participants reported using a mix of tools—including OneClick LCA, SimaPro, and Excel templates linked to BIM data—but felt that current levels of automation and interoperability are insufficient. As P5 (UK) concluded, "*The software needs to be better aligned to depend less on the way the BIM model is done.*"

Another limitation widely discussed was the manual and repetitive nature of the mapping between the Bill of Quantities and LCA databases. P2 (Bulgaria) and P4 (Italy) described this process as tedious and prone to misalignment. To address this, participants discussed the creation of BIM object libraries embedded with environmental data (e.g., pre-linked to verified EPDs), machine-readable EPD databases structured around standardised classification codes, which would allow automated matching with BIM components.

Participants also noted that current tools are not sufficiently proactive. Most BIM-LCA solutions do not provide suggestions for improving

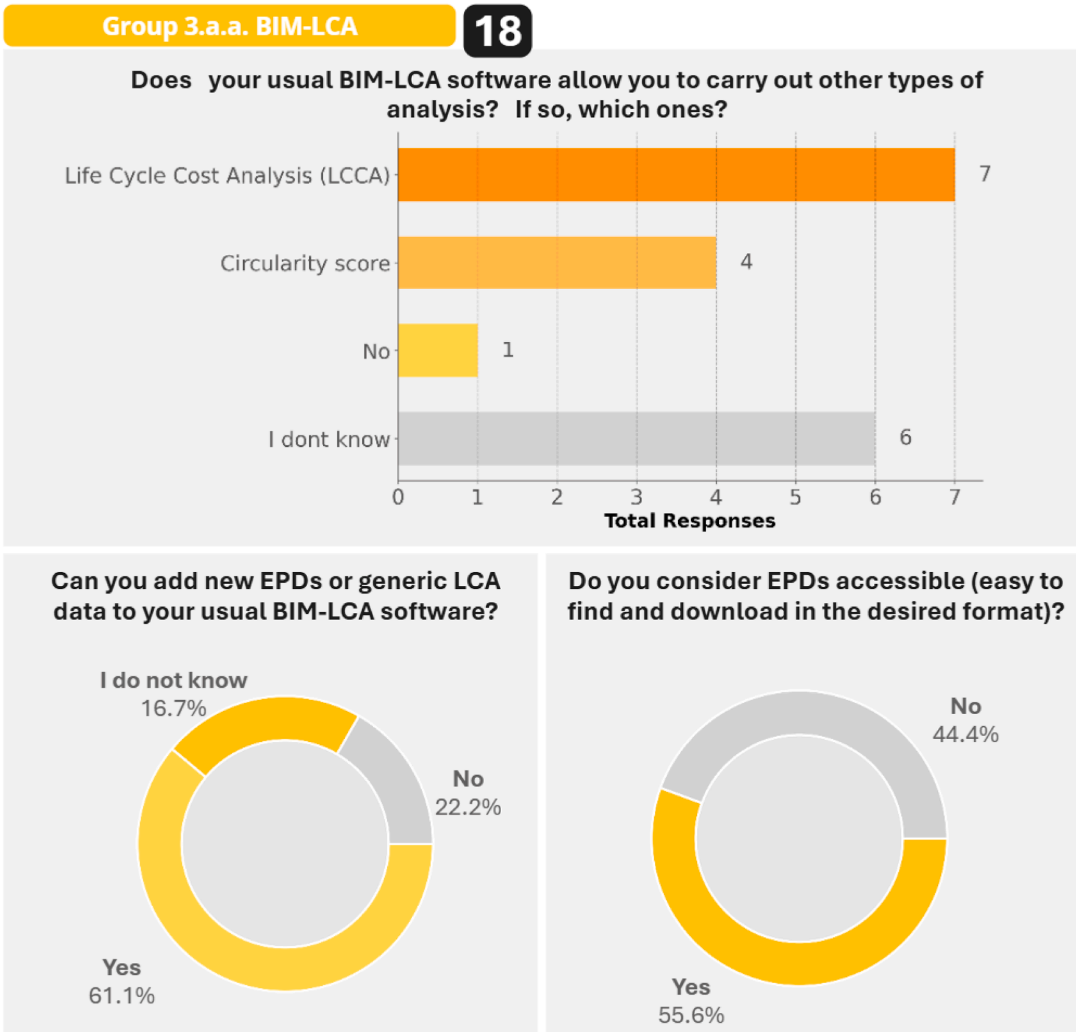

Fig. 19. Holistic assessment of BIM-LCA tools, including support for the addition of EPDs and the accessibility of EPD data.

environmental performance. OneClick LCA was the only tool mentioned that offers benchmarking at the building level. However, even this functionality was considered limited by some, as it does not integrate seamlessly with dynamic design feedback or support early-stage exploration.

There was a shared view that for automation to become effective, both BIM models and LCA datasets must become machine-readable and semantically enriched. Participants highlighted the importance of developing shared data standards and common data environments that support AI-driven applications in design. As one participant (P1) summarised, BIM-LCA is still in its infancy, but the potential for intelligent automation is significant—provided the underlying data structures are standardised and interoperable.

3.2.6. *Decision-making methods*

Participants reported that, in addition to Life Cycle Assessment (LCA), other sustainability indicators—such as LCCA, circular economy metrics, and Design for Disassembly (DfD)—are also considered when comparing design strategies. However, in practice, these evaluations are typically performed informally and rely heavily on professional judgement rather than structured methodologies. As P4 (Italy) explained, "*Trade-off evaluation is often based on simplified metrics or just a spreadsheet to assess the cost-benefit of sustainability measures*".

Only participants involved in academia or research reported using MCDA or Multi-Objective Optimisation (MOO). For example, P1 (Denmark) noted: "We use parallel coordinates and scenario comparison with students. It helps them understand the compromises, such as choosing between lower embodied carbon and better energy performance."

Such methods are rarely implemented in professional practice due to their technical complexity, additional modelling effort, and the lack of integration into commercial tools. Even when advanced features do exist—such as Monte Carlo sensitivity analysis included in SimaPro—-they typically require advanced expertise.

The group agreed that decision-making in sustainable design would benefit greatly from integrated BIM-based tools capable of assessing environmental (LCA), economic (LCC), and circularity indicators in tandem. Desired features include: (1) Visualisation of trade-offs between alternatives; (3) Real-time impact feedback; (4) Support for balancing competing criteria trough prioritisation and/or optimization; (5) Compatibility with parametric and early-stage design tools.

To achieve broader adoption, such tools must be intuitive, interoperable, and embedded within standard design practices. Until then, sustainability trade-offs will likely continue to be assessed through spreadsheets and individual expertise, limiting the potential for data-driven, optimised decision-making.

4. Literature and Empirical Results Discussion

Survey and focus group results indicate that the adoption of BIM and

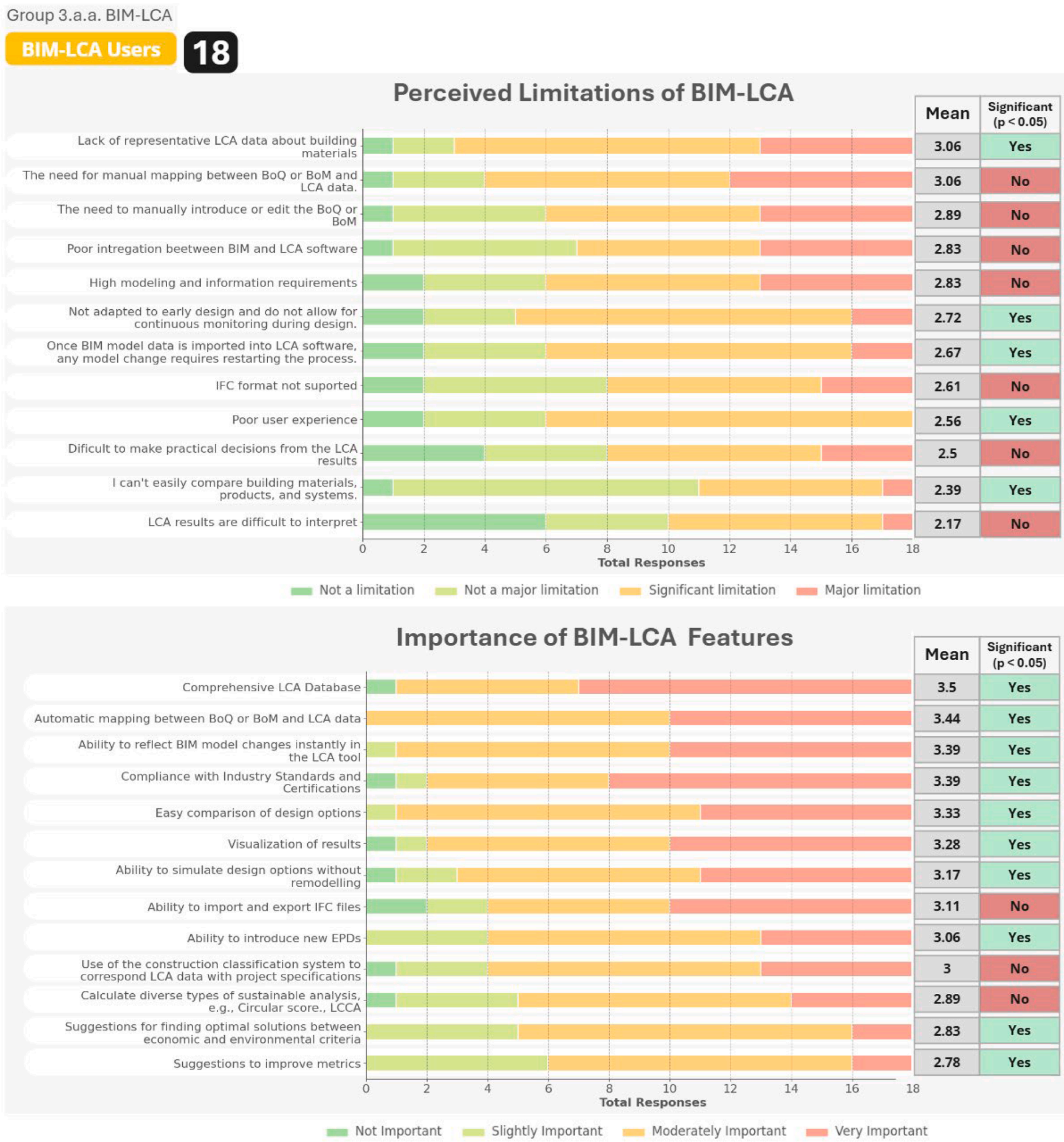

Fig. 20. Limitations and importance of BIM-LCA features.

LCA remains immature within the AEC sector. Only 29% of respondents reported using BIM-LCA tools, but higher than 9% reported globally in 2020 [38] and 12% in a 2022 New Zealand study [33].

Among those with experience in LCA, 64% reported using BIM to support LCA workflows. Of the remaining 36%, 70% acknowledged that BIM could slightly or moderately enhance LCA—particularly during the LCI phase—but do not currently use it. Notably, 70% of these non-users expressed an intention to adopt BIM-LCA tools soon. However, only 10.7% of all participants believed that BIM significantly improves LCA performance.

BIM-LCA is the preferred strategy among BIM users, while conventional LCA remains common among those without BIM experience. Furthermore, 22.6% of respondents reported having no prior experience with either BIM or LCA, indicating a general lack of knowledge or possible resistance to digital sustainability practices. This group is not confined to small firms: 35.5% are employed in large organisations and may struggle to comply with forthcoming national and European environmental regulations.

While BIM is still largely perceived as a visualisation tool, other functionalities are also used to varying degrees, including QTO, energy simulations, embodied carbon estimation, and clash detection. This is consistent with previous findings [36]. Although 82.2% of participants reported implementing sustainable building practices, only 45% of these confirmed direct involvement in LCA calculations. In most cases, LCA is performed at the end of the design process to comply with GBCs, regulatory (e.g., the revised EPBD 2024) and green public procurement, as also found by 2022 New Zealand study [33]. LCA during early-stage and continuous monitoring of environmental impacts throughout design remain rare, despite during the early phase, project decisions are the most impactful and least expensive to alter.

Both LCA users and non-users reported similar barriers to adoption. The most critical include the lack of representative LCA data, the

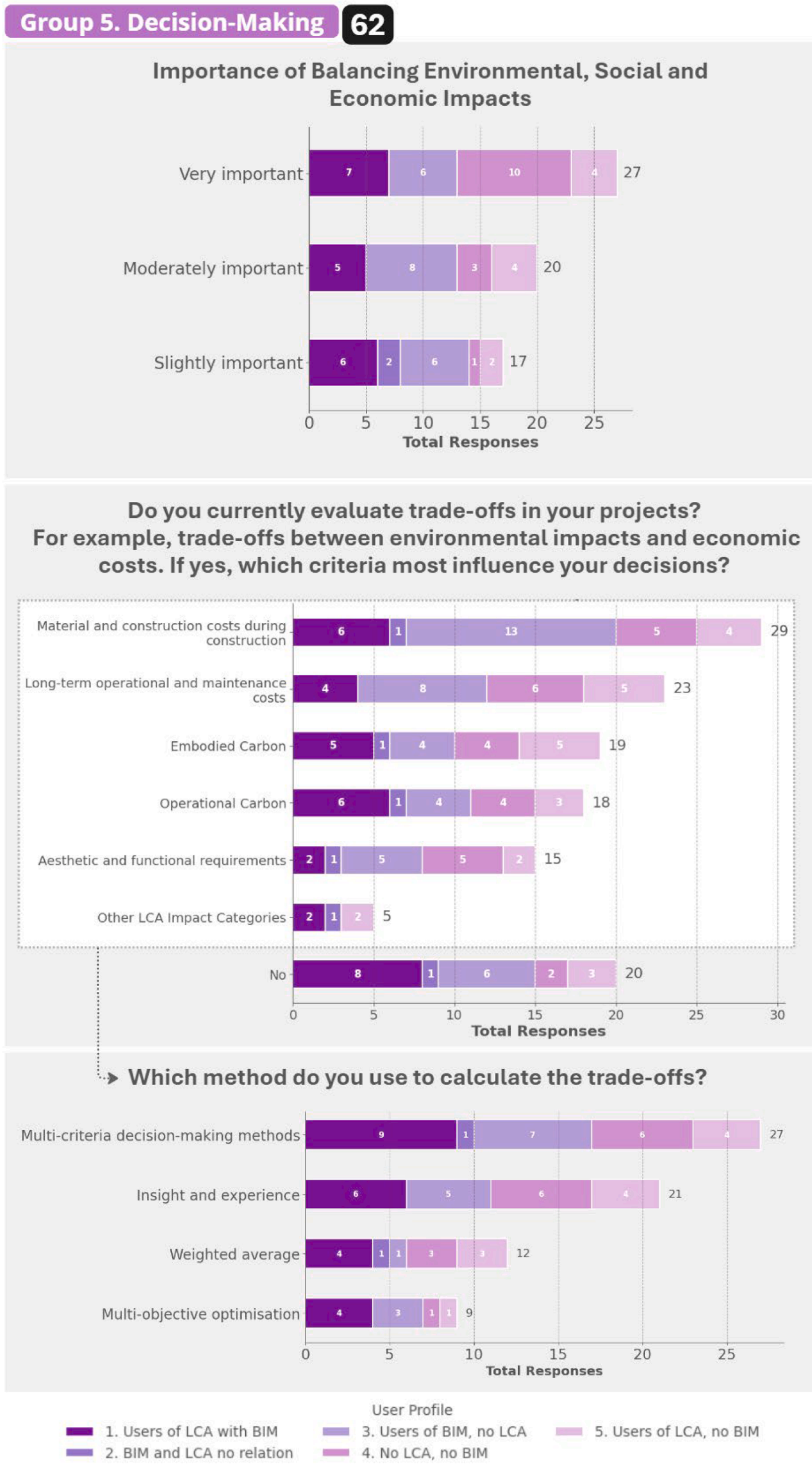

Fig. 21. Decision making methods used and criteria considered.

absence of national Environmental Product Declarations (EPDs), and low client demand. Notably, a 2011–2012 survey identified client demand as the most significant barrier to LCA adoption [33]. While it remains a relevant constraint, its relative importance may be decreasing.

BIM-LCA adoption is further hindered by a lack of comprehensive environmental databases within commercial tools, limited interoperability, manual and repetitive processes, high information requirements, and insufficient support for early-stage design iterations. Additionally, current tools often lack an interactive process (real-time feedback) aligned with typical design workflows, making their integration into daily practice inefficient.

Table 4 maps these empirical findings against the core constructs of the Technology Acceptance Model (TAM).

Table 5 synthesises the main challenges and barriers faced by BIM-LCA end-users (RQ2), identified through the survey and focus group. These are contextualised against recent academic developments used to define future research priorities aimed at supporting user-oriented BIM-LCA development (RQ3). Building on a previous systematic review [17],

Table 3
Characterization of focus group participants.

Participant	Country	Current Role/Position	Professional Background	LCA Experience	BIM Experience
P1	Denmark	Associate Professor	Building energy simulation, LCA research	Academic and applied use of building LCA	Uses BIM in teaching and optimisation
P2	Bulgaria	Sustainability Consultant	GBCs, former BIM modeller	Two years' experience in whole-building LCA	Four years as a BIM modeller
P3	Italy	Researcher	Civil engineering and building management	Research on circular economy and stakeholder data flows	Uses IFC extraction for LCA purposes
P4	Portugal	LCA Specialist, private company	Civil engineering, environmental compliance	Extensive LCA in buildings and other sectors	Experience in BIM-based quantity take-off
P5	United Kingdom	Independent Sustainability Consultant	Architecture, LEED/BREEAM, LCA, Circularity	Conducts LCA for WLC compliance in London	Works with BIM and certification systems
P6	Portugal	Architect and Academic	Architecture, building design	Theoretical and methodological knowledge	No experience in BIM but commented on the use of MCDA and data benchmarking

Table 4
BIM-LCA Adoption Mapped to TAM Constructs.

TAM Construct	Survey Findings	Focus Group
Perceived Usefulness (PU)	• Only 10.7% of non-users believe BIM significantly improves LCA. 70% believe it could be slightly or moderately enhanced. • 80% of non-users see BIM-LCA potential in BoQ extraction; 70% in data mapping; 60% in design comparison. • BIM-LCA is the preferred strategy among BIM users, whereas conventional LCA remains prevalent among non-BIM users.	• BIM-LCA seen as valuable mainly for certification compliance (e.g., BREEAM, LEED). • Not yet perceived as a true design support tool.
Perceived Ease of Use (PEOU)	• 50% of users manually edit the BoQ due to inconsistencies • 27.8% manually map LCA and BIM data in every interaction; only 22.2% used semi-automated mapping. • Most common tools used: OneClick LCA, Tally, Excel exports. • Major limitations: lack of a comprehensive database, low interoperability, manual processes involved, high information requirements, not adapted to early design LCA and continuous monitoring of impacts. • No real-time dynamic feedback, every time a BIM model is changed, we need to reimport all data and restart progress (data loss). • No Parametric design functionalities that enable rapid evaluation of alternative solutions.	• BIM-LCA described as tedious and error-prone, largely due to the insufficient semantic structuring and incomplete information content of BIM models. • Lack of clear information requirements in BEP. • Tools do not provide performance suggestions or benchmarking targets. • Manual mapping of BIM and LCA data burdens. • Strong demand for tools with real-time feedback, prioritisation and optimisation of design solutions.
Behavioural Intention (BI)	• 66.7% of LCA users already apply BIM-LCA tools (e.g., OneClick, Tally, custom Excel), but believe that they should be improved. • 70% of non-users expressed intention to adopt BIM-LCA tools soon.	• Willingness to adopt more automated and interoperable tools that align with design practice. • BIM-LCA seen as promising but not yet mature. • Participants called for integrated decision-making features, while stressing that tools should support—not replace—expert judgement.

the analysis compares empirical evidence with the literature to expose unresolved technical challenges and outline viable future directions.

4.1. LCA data

The most cited challenge of BIM-LCA is the lack of representative and context-specific environmental data for building materials. Current practices often rely on generic databases such as Ökobaudat (Germany), ICE (United Kingdom), or Ecoinvent (Switzerland). However, reliance on generic databases can result in deviations exceeding ±50% across the various environmental impact categories compared with EPD databases [50].

Although national databases such as INIES (France) and B-EPD (Belgium) offer more specific EPDs, their coverage remains limited. According to Construction LCA's *Guide to EPDs* [54], over 13,000 verified EPDs in compliance with EN 15804 were available at the beginning of 2024, yet these primarily cover finishing products [55]. For instance, in Portugal, where most study participants are based, the DAPHabitat database currently includes only 67 EPDs for locally manufactured construction materials and products [51].

With the EU advocating for mandatory carbon reporting through the revised EPBD, it's crucial to make EPDs mandatory for all construction product manufacturers to ensure data availability and reliability. While the 2024 revision of the Construction Products Regulation (CPR) marks a step forward by mandating the disclosure of GWP for all construction products from 2026, the requirement to report additional impact categories aligned with EN 15804+A2 will only come into force by 2030 [56].

On the other hand, EPDs should be embedded directly into BIM and LCA environments using standardised, machine-readable formats such as XML or JSON-LD [57,58]. However, digital EPDs are limited, and significant limitations persist in transferring digital EPDs into BIM and LCA software without manual intervention due to inconsistencies in formatting, terminology, and metadata structure. The InData network has supported the development of machine-readable EPD/LCA formats to address these interoperability issues [59]. Furthermore, harmonising the descriptive language used within EPDs, and the associated Product Category Rules (PCRs) is crucial to reducing result variability and improving data comparability.

4.2. BIM-LCA during early design and continuous assessment

Participants emphasised the need to integrate LCA earlier in the design process, noting that moving beyond compliance and using it to actively inform design decisions is key to improving environmental performance. However, this is rarely done in practice, as most available BIM-LCA tools impose high information requirements that cannot be met during early design stages, due to the significant time and financial effort involved. Most BIM-based LCA tools are designed to support detailed projects and do not limit input data according to the design phases. On the other hand, the use of specific tools for each design phase

Table 5
RQ2 & RQ3 – Challenges to BIM-LCA Implementation, Literature Approaches, and Future Research Directions.

Topic	Challenges and Barriers (RQ2)	What has already been done in academia and policy (RQ3) Based on [18].	What needs to be further done (RQ3)	
			Action type	Action
LCA data	▶ Lack of representative LCA data about building materials	▶ Generic LCA datasets (e.g., Ökobaudat, ICE, Ecoinvent). ▶ National databases with limited EPDs (e.g., DAP, in Portugal INIES in France, B-EPD in Belgium). ▶ The 2024 revision of the Construction Products Regulation (CPR) mandates that, from 2026, the GWP of products must be reported, and by 2030, additional environmental impact categories in accordance with EN 15804+A2.	**Policy & Regulatory**	Mandatory EPDs for all construction products across Europe, covering the whole life cycle and a comprehensive set of environmental impact categories.
			Data & Standardisation	Digital and machine-readable EPDs.
BIM-LCA during early design and continuous LCA	▶ It is difficult to perform an LCA during early design and to influence decisions ▶ BIM-LCA is not adapted to continuous impact monitoring throughout design. ▶ Not flexible to support different LODs.	▶ Predefined F&T for prefabricated building projects [55], [56]. ▶Use absolute BIM quantities + relative material quantities from a database (parametric modelling) [57], [58], [59]. Real time control of variables [41]. ▶Use a knowledge database containing all the necessary data, such as technical material and LCA data [60], [61]. ▶ Implement a hierarchical database correlated to the LOD and LCA data type (i.e., generic, average and specific data) [62]. ▶ Use minimum and maximum GWP for building assemblies in early design [63] [62]. ▶ Use EPDs with Range Factors (min, max, avg, median) in early design [63].	**Automation & Digital Tools**	The academic developments should be reflected in commercial tools (parametric modelling, hierarchical databases …)
			Automation & Digital Tools	ML to learn from past projects to apply typical assumptions for placeholder materials during the early design
			Automation & Digital Tools	ML to predict environmental impacts during early design.
			Automation & Digital Tools	Develop a dynamic data extraction approach independent of proprietary BIM software, able to store and track project history. *
			Data & Standardisation	Standardise LOD for different LCA applications (Screening, Simplified, Complete LCA); and

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Table 5 (*continued*)

		▶ Use dynamic data extraction, as this allows model changes to be automatically reflected in the LCA results. ▶ Conduct sensitivity analyses to understand the impact of each design variable in each design phase.		assess uncertainty based on the LOD/LOIN of BIM objects.
			Data & Standardisation	Create local databases with typical construction assemblies and processes.
Automation during LCI	▶ Inadequate modelling ▶ Mistakes and modelling outside of industry standards introduce inaccuracies ▶ Editing the BoQ or BoM is time-consuming. ▶ BIM-LCA software is not aligned with the designer's workflow ▶ BIM model changes typically require restarting LCA calculations (data loss). ▶ Not allow real-time and dynamic feedback	▶ In academic research, custom BIM-LCA tools and models are developed to meet exchange requirements and standardise information management with defined LOD/LOIN. ▶ To complement the BIM model, use a knowledge database containing all the necessary data, such as technical material and LCA data. ▶ Model View Definitions (MVD) for LCA and Product Data templates [64], [65], [66]. ▶ Dynamic/static data extraction methods with real time BIM changes in LCA results [66].	**Data & Standardisation**	Define LOD and BIM uses in the EIR and BEP. The appointing and appointed parties should have prior access to the information requirements.
			Automation & Digital Tools	BIM validation tools to ensure models are compatible with quantity take-off for LCA.
			Automation & Digital Tools	Develop a dynamic data extraction approach independent of proprietary BIM software, able to store and track project history. *
Automation during LCIA	▶Time-consuming manual mapping between BoQ or BoM and LCA data.	▶ Data structure through a Construction Classification System (CCS) and naming conventions [57].	**Automation & Digital Tools**	Further research ML algorithms for object classification and LCA data assignment.

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Table 5 (*continued*)

	▶ Difficulty modelling overlooked lifecycle phases (e.g., A5, B1, B3, C1) due to high uncertainty.	▶ML for BIM object classification & LCA data assignment [60].	**Automation & Digital Tools**	Use ML to classify the available LCA, LCC and S-LCA databases. Classify EPDs and new entries for these databases with CCS.
			Automation & Digital Tools	Further research Web technologies to connect BIM with LCA data and enable SPARQL-based queries.
			Data & Standardisation	Create a national database to define average energy use and waste generation per construction and deconstruction activity.
Renovation Projects	▶ Renovation and retrofit projects are seen as more challenging.	▶ Generation of multiple renovation scenarios & identifying renovation measures for each building element [67]. ▶ Scan-to-BIM approaches to identify the existing structure [68].	**Automation & Digital Tools**	Machine Learning for classification of point cloud data.
			Automation & Digital Tools	ML models to predict end-of-life scenarios based on material degradation and component interdependencies.
			Data & Standardisation	Standardised property sets (Psets) and data templates for renovation-specific BIM/IFC attributes.
Education	▶ Lack of experienced professionals ▶ Professionals with limited LCA experience don't know the difference between LCIA methods and assumptions.	▶ Capacity-building initiatives and incentives for companies to train their workforce. ▶ BIM-LCA tools must communicate all assumptions and LCA modelling choices to avoid misunderstanding.	**Education & Skills Development**	Mandatory BIM and LCA modules in academic curricula and continuing education programmes.
			Education & Skills Development	Online platforms for ÇCA and BIM-LCA concepts learning.
Interpretation and	▶ Results are not easily understood; therefore,	▶ Use of MCDA and MOO methods to prioritise and identify optimal solutions	**Decision-making**	Use meta-models to reduce MOO computation.

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Table 5 (*continued*)

Decision Making	they don't support design decisions.	across multiple sustainability indicators.		
	▶ Lack of regional/local benchmarks to guide designers.	▶ Few studies applied a meta-model to approximate GWP based on design variables and reduce the computational load of MOO [69]. Few studies applied parametric modelling and ML to benchmark each component's min/max impact [70].	**Decision-making**	Use parametric design and ML to benchmark each building component and define the minimum and maximum LCA impacts (predictive modelling).
	▶ No standardised way to report LCA results with uncertainty ranges	▶ BIM-based tools for LCSA (LCA + LCC+ S-LCA) including other indicators from Leve(s) framework,	**Decision-making**	Apply ML—such as reinforcement learning—to suggest design improvements and alternatives at the component and building levels.
		▶ Uncertainty analysis in building LCA—e.g., via Monte Carlo simulations. But it may be too complex for non-experts. A clear strategy for treating and communicating uncertainty in building LCA is still lacking, as noted by [41].	**Decision-making**	Combine continuous LCA, dynamic real-time feedback, meta-models, MOO, and MCDA to support integrated and iterative decision-making
			Data & Standardisation	Develop a regional database by building LCA results for benchmarking and defining budget-based targets scaled to a regional, national or European reference (material, component and building level).

*Repeated entry - applies to multiple BIM-LCA topics.

results in workflow interruptions and data loss.

To address uncertainty and facilitate early design LCA, researchers have proposed various solutions. One is the use of predefined families and types and BIM templates for prefabricated buildings during early design [60,61]. Another involves creating libraries of typical construction assemblies, aligned with national standards and construction practices. These can serve as proxies in early-stage LCA by providing relative material compositions and enabling parametric modelling based on absolute BIM quantities [62–64]. Parametric controls—such as sliders or inputs for material thickness—can further enhance flexibility [40].

Other authors have proposed a knowledge database containing all the necessary data, such as technical material and LCA data [65], and hierarchical LCA databases aligned with different LOD and LCA data types (e.g., generic, average, specific LCA databases) [66]. These databases may also incorporate construction classification systems, which are often hierarchical—organised by building functions, systems and products supporting a progressive refinement of results as the design evolves [62]. On the other hand, Palumbo et al. [67] also suggest using EPDs with statistical range factors (e.g., minimum, average, maximum values) to address uncertainty when project-specific data is not yet available.

Moreover, Meex et al. [39] recommend storing all design alternatives to prevent data loss between iterations and introducing real-time feedback mechanisms—such as interactive dashboards tracking carbon emissions—to integrate LCA iteratively within design processes.

Despite growing academic attention on early-stage and continuous performance monitoring [68–71], these features remain largely absent in commercial tools. To the authors' knowledge [17] only Autodesk Forma and Carbon Designer (by OneClick LCA) currently support early design integration, and even these tools have limited scope. Academic BIM-LCA tools are typically early-stage prototypes (Technology Readiness Levels, TRL 1–3) developed in controlled with enriched datasets, lacking the robustness, testing, and integration demanded by commercial markets. Bridging to TRL 6-7 entails significant time and cost [72].

Despite these academic developments, further solutions must be explored. Machine learning (ML) techniques hold significant promise in early-stage design, where data is often incomplete. ML models trained on historical project data can infer plausible assumptions for placeholder materials or predict environmental impacts for partially defined elements. On the other hand, ML can be used to predict environmental metrics (*e.g.*, GWP, embodied energy) directly from geometric or sematic inputs using neural networks or regression-based models. However, as Hollberg [73] notes, such methods depend heavily on access to extensive datasets of as-built BIM models linked to LCA outputs.

In parallel, standardising LOD for various LCA applications—such as screening, simplified, or complete LCA—as defined in the EeBGuide Handbook (*cit.* [19,74]), might facilitate a more structured and integration of LCA throughout the design process, by establishing a clear link between model inputs and the evolving level of project development [75]. Assessing uncertainty according to the LOD of BIM objects is also essential. Lower LODs rely on estimated quantities and are typically associated with generic LCA data, which significantly increases uncertainty. The relationship between LOD and data quality is critical for decision-making, as it directly influences the level of confidence in comparing design alternatives. Therefore, aligning LOD definitions with uncertainty thresholds and information requirements across BIM-LCA tools and existing industry standards is crucial to support reliable and risk-aware decision-making [76].

4.3. Automation during LCI

Several users with experience in conventional LCA reported unsuccessful attempts to adopt BIM-LCA tools, citing errors in the BoQ and the time-consuming nature of manual corrections. Among participants who reported using BIM-LCA, 64% indicated that they must manually edit the BoQ, most commonly for elements such as walls, floors, windows, railings, stairs, ramps, and roofs. These issues were often caused by inconsistent object naming, incorrect classification, and BIM models that did not meet the necessary information requirements.

[62] In a well-structured BIM process following ISO 19650-1 [47], the intended BIM Uses, such as LCA, are explicitly defined in the project's Exchange Information Requirements (EIR) by the appointing party and then detailed in the BIM Execution Plan (BEP) by the appointed party. The BEP specifies the geometry and information needs for each project phase and assigns responsibilities accordingly, ensuring that BIM models are developed in alignment with the data requirements of the selected BIM-LCA tool. These requirements should be consistent with the scope, goal and application of the LCA (e.g., screening, simplified, or complete), and aligned with the design phase, as discussed in the previous subsection.

Both the appointing and appointed parties must have access to the information requirements of the chosen BIM-LCA tool, which can help standardise the structure and content of BIM models. Model-checking tools can be employed to detect issues such as unclassified objects, missing parameters, and clashing or incorrect geometry prior to LCA execution.

In addition, dynamic data extraction methods—allowing real-time synchronisation of BIM model changes within the LCA environment—can substantially reduce rework. However, such functionality is typically only available through add-ons, visual programming scripts, or BIM templates, depending on proprietary BIM software. In contrast, static data extraction benefits from using Global Unique Identifiers (GUIDs) assigned to each object. If GUIDs remain unchanged between IFC versions, LCA software can retain links to environmental data, avoiding the need to manually re-map quantities and geometric information after each model update.

In the context of IFC, Information Delivery Manual (IDM) and Model View Definitions (MVDs) should be developed for LCA as they ensure that Information requirements are meet [77,68]. In parallel, BIM objects should follow Product Data Templates (PDTs) to facilitate the structured extraction, enrichment, and updating of object attributes.

Ultimately, greater automation in the LCI phase depends on three interrelated factors: high-quality and standardised BIM modelling practices, and accessible and well-organised LCA data for structured information exchanges. Advancing these aspects requires increased BIM maturity among stakeholders and broader adoption of standardised modelling protocols across the industry.

4.4. Automation during LCIA

Participants identified the LCIA phase as highly manual and time-consuming. Assigning generic LCI data or EPDs to each material or product becomes increasingly complex and error-prone, particularly in large or evolving BIM models and projects. This is primarily due to the absence of shared data structures between BIM objects and environmental databases.

To address this challenge, several authors have proposed the use of Construction Classification Systems (CCS) and consistent naming conventions. For example, Alvarez et al. [78] linked BIM objects to LCA and LCC databases using assembly codes, while Parece et al. [62] used the SECCLasS CCS, derived from Uniclass, and Li et al. [64], applied the Chinese Standard for BIM Classification (GB/T 51269-2017). Additionally, Cang et al. [79] developed a custom code structure, and Naneva et al. [80] used the Swiss eBKP-H cost-planning codes to connect BIM elements with LCA data.

Using a CCS enables machine-readable data exchange between BIM and LCA tools, creating the basis for ML automation—although such applications are still scarce in the literature. Forth et al. [81] applied NLP to automatically match IFC elements with environmental databases. ML algorithms trained on labelled BIM data can identify object types based on geometry, naming, and embedded properties, and suggest appropriate LCA or EPD profiles. Emerging research also proposes using ML to categorise entire environmental databases—such as EPDs, LCC and S-LCA data—into structured ontologies or CCS-aligned taxonomies to streamline data retrieval and selection [76]. Additionally, integrating BIM and LCA through web-based semantic architectures—using technologies such as SPARQL queries, linked open data, and domain ontologies—could provide further benefits, such as dynamic querying of external LCA repositories directly from BIM environments [82].

Another key gap relates to modelling life cycle stages such as construction (A5), use phase impacts (B1, B3), and end-of-life processes (C1–C4), which are often neglected due to the lack of structured and reliable data. One possible solution is to develop national or regional databases that define average energy use and waste generation per construction or demolition activity. At the same time, mandatory cradle-to-grave EPDs from manufacturers can significantly improve the completeness of LCIA results across all modules of the building life cycle.

Additionally, this study found that several BIM-LCA tool users were unfamiliar with LCA concepts and could not clearly distinguish between LCI and LCIA data. They did not understand what LCIA methods are or the assumptions behind them. While BIM-LCA tools are intended to support qualified experts, they must also be accessible to non-specialists. As such, tools should provide predefined calculation settings—including reference study periods, system boundaries, and LCIA methods—while communicating their assumptions and implications through user-friendly interfaces.

4.5. Renovation Projects

Renovation and retrofit projects pose unique challenges for BIM-LCA integration, particularly due to the limited availability of data on existing building conditions and the lack of standardised methodologies for modelling selective demolition, material reuse, and phased interventions. As participants in this study noted, renovation scenarios are often more challenging because they require additional effort to capture as-built conditions and adapt BIM models manually, and BIM-LCA do not consider the existing structure and possible interventions. A critical aspect of LCA of renovation projects is the high level of information required. BIM models typically need to reach LOD 400–500 to enable the identification of individual components, their physical condition, and potential end-of-life treatments.

According to Parece et al. [17] and Soust-Verdaguer et al. [83] comparatively fewer studies have addressed BIM-LCA integration in the context of renovation. One notable example is Fenz et al. [70] who developed a web-based tool capable of automatically processing IFC files of existing buildings to generate multiple renovation scenarios.

Other research has investigated the use of Scan-to-BIM methodologies. For example, Kim et al. [71] employed 3D laser scanning to generate point clouds, which were then used to develop accurate BIM models that reflect the as-built state of buildings and their components. These models were subsequently enriched with LCA-relevant attributes to support more precise environmental assessment.

In addition, integrating ML with Scan-to-BIM workflows offers the potential to automate the identification, classification, and condition assessment of building elements within point cloud data [17].

4.6. Education

The survey revealed that although many participants had been involved in LCA and BIM-LCA workflows, a significant number lacked understanding of fundamental concepts—such as the phases of LCA as defined by ISO 14040, or the differences between various LCIA methods. This highlights that, in addition to developing user-friendly tools tailored to non-LCA specialists, greater investment in training is essential. Embedding life cycle thinking within the AEC sector requires mandatory BIM and LCA education in both academic curricula and continuing professional development programmes, supported by accessible digital learning resources.

4.7. Interpretation and decision making

A key barrier to effective use of BIM-LCA identified in this study is the difficulty in interpreting environmental assessment results in a way that supports meaningful design decisions. Although BIM-LCA tools provide quantitative data, many users struggle to understand and apply the outputs, particularly those without LCA expertise. As noted by Meex et al. [39] when results are presented exclusively through midpoint impact categories (e.g., GWP, EP, ODP), which fail to connect with practical design goals. Using a single impact category may be sufficient in targeted studies, but this approach can lead to suboptimal solutions.

For simplified LCAs, the set of indicators defined by EN 15978—including GWP, EP (Eutrophication Potential), AP (Acidification Potential), ODP (Ozone Depletion Potential), POCP (Photochemical Ozone Creation Potential), and ADP (Abiotic Depletion Potential)—should be considered. Input-related parameters such as PET (Primary Energy Total) and PENRT (Non-renewable Primary Energy) are also recommended.

According to Meex et al. [39] and Kägi et al. [84], most designers prefer a single aggregated environmental impact score at the building level, supported by more detailed information at the component or life cycle stage level. Several national initiatives have adopted this approach. In Switzerland, for example, the *Umweltbelastungspunkte* (Environmental Impact Points) method presents results in a single score. In Belgium, the Environmental Impact Score (*Totale Milieuscore*) aggregates LCA impacts using monetary weighting, resulting in values expressed in euros (€). In the Netherlands, the *MilieuPrestatie Gebouwen* (MPG) expresses environmental impact as a monetised value per square metre per year (€/m^2·year), using shadow prices across impact categories.

Participants in this study also expressed the need to combine LCA with other design indicators, such as LCCA, Social LCA (S-LCA), construction cost, circular economy metrics, and energy efficiency. However, as concluded by Parece et al. [17], these holistic assessments are rarely integrated into current BIM-LCA tools, and decision-making frameworks such as MCDA, MOO, sensitivity or uncertainty analysis are seldom embedded in practical workflows.

When properly implemented, MCDA can prioritise design alternatives based on project-specific preferences, while MOO enables the identification of optimal trade-offs across conflicting criteria such as carbon, cost, and circularity. Hybrid approaches combining MCDA and MOO offer a structured and computationally efficient framework for supporting complex decision-making [17]. To further reduce computational demands and enable real-time feedback, some studies suggest the use of surrogate models (ML algorithms) trained on parametric simulations [85].

Another persistent challenge is the lack of regional or local LCA benchmarks, which makes it difficult for practitioners to assess whether a design performs above or below typical values in a given context and region. Proposed solutions include the creation of national databases of material, component, and whole-building LCA results to enable carbon budgeting and performance targeting. In parallel, parametric modelling and ML can simulate material combinations across design options to establish minimum and maximum impact values for each component and suggest improvements [86] and alternatives by learning from historical project data.

Finally, uncertainty in BIM-LCA results remains a major concern. Currently, commercial tools have no standardised way to represent or communicate uncertainty ranges. Although Monte Carlo simulations and sensitivity analyses are frequently cited in academic literature, they are rarely implemented in practice due to their complexity. BIM-LCA tools must incorporate clear, accessible strategies for communicating uncertainty, data assumptions, and confidence levels.

Looking ahead, a promising direction for BIM-LCA tools is the integration of continuous performance monitoring with dynamic data extraction and AI-enhanced decision-support methods (e.g., combine surrogate models, MOO, MCDA) [17]. This would enable real-time feedback as the design evolves, allowing users to track environmental impacts continuously, respond to changes instantly, and optimise trade-offs across multiple criteria—directly within the design environment [17].

5. Sample Limitations and Bias Considerations

The survey is not statistically representative of the entire construction sector but offers practitioner-informed insights from professionals with practical experience or knowledge in LCA and sustainable construction. Although exploratory and based on a limited sample (n = 62), several measures were adopted to mitigate potential sources of bias and enhance the trustworthiness of the findings.

Of the 62 respondents, 38 were based in Portugal; however, 56% of these work in internationally active firms, suggesting that their perspectives reflect European regulations, standards, and transnational market dynamics. Nevertheless, this geographic concentration may reflect context-specific regulations or norms that do not generalise across Europe.

Methodological strategies—such as branch logic to reduce respondent fatigue and anonymous participation to minimise social desirability bias—were employed to improve response quality. The diversity of question formats (e.g., Likert scales, binary, and open-text items) limited the scope for standardised statistical modelling but facilitated richer qualitative interpretation. This limitation is particularly pertinent in survey sections answered by smaller subgroups, such as those with only 18 responses concerning BIM-LCA tool use. Nonetheless, cross-validation with focus group findings added qualitative depth and enhanced the interpretive validity of the results.

To address central tendency bias, two Likert scales were used: a 5-point scale (including a neutral midpoint) for broader questions answered by 34 respondents, and a 4-point forced-choice scale for BIM-LCA specific questions answered by 18 respondents. While the latter encouraged clearer positions, it may also have constrained the expression of uncertainty or created artificial polarisation.

These considerations do not undermine the relevance of the findings but underscore the importance of interpreting them as indicative trends and as practitioners' insights rather than statistically generalisable conclusions.

The sample was predominantly composed of professionals in design, engineering, and consultancy group (93.5%), with limited representation from contractors, developers, or building owners. This reflects the current profile of BIM-LCA users, who are typically responsible for design, modelling, and environmental assessment tasks. However, it also limits the representativeness of perspectives across the full construction value chain. The inclusion of regulatory bodies or industry associations could have added a broader policy dimension. Nevertheless, the focus of this study was to capture the practical experiences and challenges faced by active tool users—an aspect still underrepresented in the literature.

6. Conclusion

This study investigated BIM-LCA adoption and user challenges through a survey (n = 62) and focus group (n = 6). The empirical findings were cross-referenced with recent advances reported in a previous systematic review by Parece et al. [17], providing insights to inform future research and support the development of user-oriented BIM-LCA solutions. Although based on an exploratory sample, the results offer valuable practitioner perspectives.

Findings revealed that LCA is still primarily applied at later stages of design and driven by Green Building Certification (GBC) requirements, with limited use during early design to guide design decisions. BIM-LCA is the preferred strategy among BIM users, whereas conventional LCA remains prevalent among non-BIM users.

Notably, users of BIM-LCA tools reported significant difficulties arising from the lack of integration between BIM environments and LCA software. Challenges included the absence of comprehensive environmental databases, repetitive and manual processes (e.g., editing BoQs, mapping BIM objects to LCA data), high information requirements, and insufficient support for early-stage iterations. The absence of dynamic feedback and frequent data loss during model updates were also highlighted. For LCA experts, interpreting results is further hindered by the lack of benchmarks, unclear modelling assumptions, and inconsistent communication of uncertainty.

These findings were mapped to the core constructs of the Technology Acceptance Model (TAM), helping to assess perceived usefulness, ease of use, and behavioural intention.

Building on a previous systematic literature review [17], the study aligned practitioner-reported challenges with recent academic and regulatory developments, identifying seven priority areas: LCA data; BIM-LCA in early design and continuous monitoring; automation during LCI and LCIA; renovation projects; education and skills; and interpretation and decision-making. Actions were structured across four domains: Policy & Regulation, Data & Standardisation, Automation & Digital Tools, and Decision Support.

Although recent academic advances—such as parametric modelling, hierarchical LCA databases, ML-driven automation, and decision-support frameworks—hold promise, they remain largely confined to academic contexts. Bridging the gap between research prototypes and commercial applications (i.e., from TRL 3 to TRL 6-7) requires further development, validation, and standardisation. Successful BIM-LCA implementation also depends on structured modelling practices and mature BIM processes. This includes the consistent use of classification systems, exchange standards, and interoperable data environments. Recurring issues—such as misclassified elements or inaccurate quantity take-offs—could be significantly reduced through collaborative modelling practices aligned with well-defined project requirements, such as those established in BIM Execution Plans (BEP) and Exchange Information Requirements (EIR).

Looking ahead, a promising direction for BIM-LCA tools is the integration of continuous performance monitoring with dynamic data extraction and AI-enhanced decision-support methods (e.g., combine surrogate models, MOO, MCDA). These features would enable real-time feedback as the design evolves, allowing users to continuously track environmental impacts, respond to changes instantly, and optimise trade-offs across multiple sustainability criteria.

This study supports the development of user-oriented BIM-LCA tools and offers valuable guidance for researchers, software developers, and policymakers. Future work should involve a broader, cross-European survey and additional focus groups covering a wider range of professional roles and regions. Expanding the sample will help validate the findings and mitigate limitations related to representativeness, thereby building a more robust evidence base to inform the development of next-generation BIM-LCA tools, standards, and policy frameworks.

Declaration of generative AI and AI-assisted technologies in the writing process

While preparing this work, the authors used Grammarly to correct the English grammar. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the publication's content.

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CRediT authorship contribution statement

Sara Parece: Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Ricardo Resende:** Writing – review & editing, Supervision, Data curation, Conceptualization. **Vasco Rato:** Writing – review & editing, Supervision, Data curation, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Sara Parece reports financial support was provided by Foundation for Science and Technology. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.buildenv.2025.113434.

Data availability

Data will be made available on request.

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