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Review Article Integrating Building Information Modelling and Life Cycle Assessment for Sustainable Structural Design: A Critical Review

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ABSTRACT

The environmental performance of buildings is influenced by decisions concerning structural systems, material quantities, construction processes, use, maintenance and end-of-life treatment. Life Cycle Assessment (LCA) provides a structured method for quantifying environmental impacts within defined system boundaries, while Building Information Modelling (BIM) stores geometric, material and quantity information that can support the preparation and updating of life-cycle inventories. This review critically examines selected research on BIM–LCA integration, with particular attention to structural material selection, automated data exchange, structural optimisation, multi-criteria decision-making and digital-twin-enabled life-cycle sustainability assessment. A targeted narrative synthesis was undertaken using the research papers assembled in the authors' source collection, supplemented by bibliographic verification of key publications. The reviewed evidence indicates that BIM-based quantity extraction and software links can make environmental assessment more iterative and accessible during design. Structural optimisation and alternative concrete mixtures can also reduce reported embodied impacts in specific case studies. However, the magnitude and ranking of results are sensitive to environmental product declaration (EPD) datasets, geographical context, model detail, functional equivalence, life-cycle modules and the treatment of biogenic carbon. Multi-criteria methods further demonstrate that the preferred option may change when cost and social indicators are included. The principal research needs are validated open data exchange, regionally representative life-cycle inventory data, transparent model-detail reporting, whole-life coverage, uncertainty analysis and validation across real projects. The review concludes that BIM is an enabling information platform rather than a guarantee of LCA accuracy; credible sustainable structural decisions require technically equivalent alternatives and transparent assessment assumptions.

Keywords: Building Information Modelling; Life Cycle Assessment; structural design; embodied carbon; environmental product declaration; interoperability; life-cycle sustainability assessment.

1. Introduction

The built environment requires substantial quantities of materials and energy, and its environmental burden extends beyond building operation. Structural systems are important within this context because concrete, reinforcing steel, structural steel, timber and other load-bearing materials are produced, transported, assembled, maintained and eventually recovered or disposed of. Decisions made during concept and detailed design influence material demand and can constrain later opportunities to reduce embodied impacts. Life-cycle thinking is therefore relevant to structural engineering alongside conventional requirements such as strength, stability, serviceability, durability, constructability and cost.

Life Cycle Assessment is a method for compiling and evaluating the inputs, outputs and potential environmental impacts of a product system throughout its life cycle. ISO 14040 and ISO 14044 establish the general principles, framework, requirements and guidelines for LCA. For buildings, assessment may be organised using life-cycle modules covering product manufacture (A1–A3), construction (A4–A5), use (B1–B7), end-of-life (C1–C4) and benefits or loads beyond the system boundary (module D). The selected boundary and functional unit determine what is included and what comparisons are valid.

BIM provides a structured digital representation of building elements and their associated properties. When material classifications, quantities and product information are linked to appropriate life-cycle inventory (LCI) datasets or EPDs, BIM can reduce repeated quantity take-off and support faster comparison of design alternatives. The integration is not automatic or inherently accurate: model omissions, inconsistent units, material naming, geographic mismatch, database quality and incomplete life-cycle coverage can all influence results. Studies have therefore investigated both the technical workflow and the organisational barriers to implementation (Asare et al., 2020; Onososen & Musonda, 2022; Klumbyte et al., 2023).

The purpose of this paper is to critically synthesise selected studies on BIM-enabled LCA for sustainable structural design. The review addresses five questions: (i) how BIM information is transferred into LCA workflows; (ii) how structural materials and design optimisation affect reported environmental outcomes; (iii) how multi-criteria methods influence material selection; (iv) how digital twins may connect design estimates with operational evidence; and (v) which technical and methodological barriers continue to limit reliable implementation.

2. Review methodology

2.1 Review design and source base

A targeted critical narrative review was prepared from the research papers and presentation material assembled by the authors. The source collection included journal articles and a 2025 conference paper addressing BIM–LCA workflows, structural carbon assessment, alternative concrete mixtures, multi-criteria sustainability assessment, structural optimisation, digital twins and implementation barriers. Key bibliographic details were cross-checked against publisher or institutional records where available. The selected papers were grouped by research contribution rather than treated as a single homogeneous dataset.

2.2 Thematic synthesis

The synthesis used five themes: (1) BIM data extraction and interoperability; (2) structural material selection and embodied impacts; (3) optimisation and multi-criteria decision support; (4) whole-life assessment and digital-twin feedback; and (5) implementation barriers and research needs. For each study, the review considered its research purpose, case-study context, modelling or analytical approach, life-cycle scope, reported contribution and limitations.

2.3 Scope and limitations of the review method

This article is a narrative review and does not claim to be a systematic review. The available team source collection does not provide a complete reproducible database-search log, search strings, duplicate-removal record or screening flow. Accordingly, no PRISMA selection count or exhaustive coverage claim is made. The studies differ in building type, functional unit, system boundary, environmental indicators and software; their numerical outputs are not pooled into a meta-analysis. Quantitative values are reproduced only where the underlying source provides a traceable case-study result, and are labelled with their original units and assessment scope.

3. BIM–LCA integration for structural design

3.1 Information flow from BIM to LCA

A BIM model can supply quantities for structural components such as foundations, columns, beams, slabs, walls, reinforcement and connections. These quantities are not yet an LCA result. They must be assigned to appropriate material or product records, converted into consistent units and combined with life-cycle inventory data. The impact assessment then applies selected characterisation factors to calculate indicators such as global warming potential (GWP), acidification potential and embodied energy. Klumbyte et al. (2023) developed an API-based workflow for whole-building LCA using information extracted from BIM files and associated data sources. Asare et al. (2020) demonstrated a design-stage process linking Revit with energy and LCA tools for a residential case in Ghana.

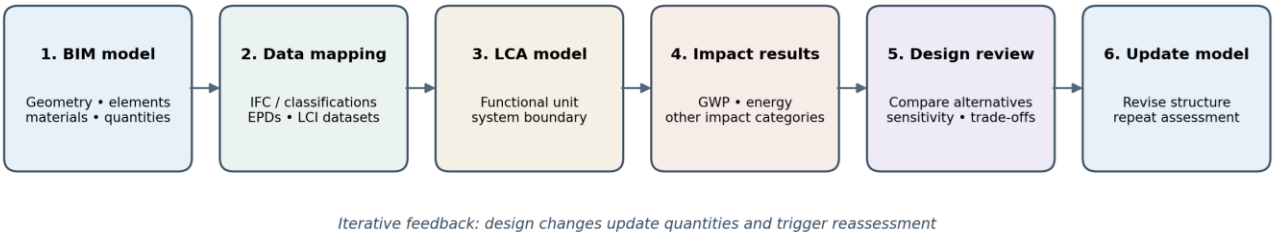


Figure 1. Conceptual BIM–LCA information workflow developed for this review. The cycle is iterative: design changes require updated quantities and reassessment.

3.2 Levels of integration

The literature commonly distinguishes manual or conventional exchange, static integration and more dynamic or bidirectional workflows (Pan et al., 2024). In a conventional workflow, quantities are exported to spreadsheets and mapped manually to LCA datasets. Static integration uses exchange formats such as IFC or software plug-ins to transfer information. Dynamic integration seeks to maintain a more continuous connection between the BIM model and assessment environment, allowing changes to propagate with less repeated data entry. The level of automation varies across the LCA stages: automating quantity extraction does not necessarily automate the selection of environmental datasets or the interpretation of impacts.

Integration approach	Typical data transfer	Potential benefit	Key risk / limitation
Conventional / manual	BIM schedules exported to spreadsheets; manual matching to LCI records	Accessible and flexible for small projects	Repeated data entry, unit errors and weak traceability
Static / plug-in or IFC	Structured model exchange or software plug-ins	More repeatable quantity transfer and model-based updates	Mapping rules and dataset selection may still be manual
Dynamic / code-based	API or bidirectional connection between BIM and assessment tools	Supports iterative design feedback and automated recalculation	Requires robust data schemas, version control and validation

3.3 Life-cycle boundaries and functional equivalence

The environmental result depends on which life-cycle modules are included. A production-stage assessment (A1–A3) cannot be directly compared with a cradle-to-grave result that includes transport, construction, use and end-of-life. The functional unit must also represent equivalent service, such as one square metre of floor area over a stated reference study period, or a structural element designed to satisfy the same loading and durability requirements. For structural comparisons, alternatives should satisfy equivalent structural performance and service life; otherwise, a lower material quantity may simply reflect a different level of function.

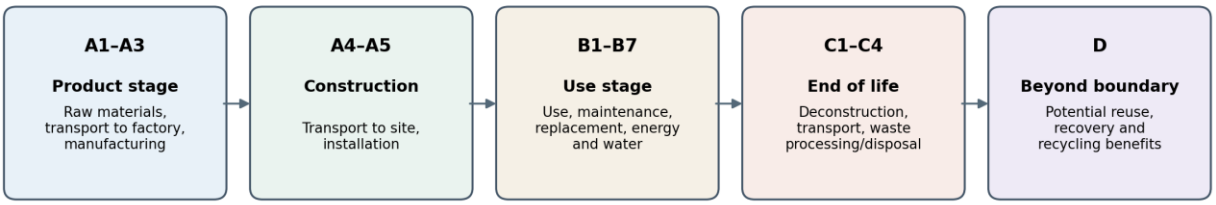


Figure 2. Simplified building life-cycle modules used to define assessment boundaries. Module D is reported separately from the building life-cycle modules.

4. Critical review of selected studies

Table 1 summarises selected studies that contribute directly to BIM–LCA methods or to structural and material decision-making. The studies provide complementary evidence, but they should not be interpreted as controlled replications because their objectives, building types, software and system boundaries differ.

Study	Approach and context	Main contribution	Important caution
Eleftheriadis et al. (2018)	BIM-embedded embodied-carbon assessment with multi-objective optimisation of reinforced-concrete building alternatives	Links structural layout and member sizing to cost–carbon Pareto alternatives; highlights building-level interactions	Case-specific product-stage carbon factors and optimisation constraints; not a universal saving rate
Marzouk et al. (2018)	BIM-based life-cycle-cost optimisation using Monte Carlo simulation and a genetic algorithm	Demonstrates BIM-supported economic optimisation and uncertainty-aware cost evaluation	LCC and LEED points are not equivalent to a full environmental LCA
Asare et al. (2020)	Revit, Green Building Studio and Tally applied to early design of a Ghanaian dwelling	Provides a design-stage guidance framework linking embodied and operational considerations	Authors note limitations in geographic representativeness of available LCA data

Study	Approach and context	Main contribution	Important caution
Soust-Verdaguer et al. (2022)	BIM-based life-cycle sustainability assessment across early and detailed design	Shows that more than 60% of LCSA inventory indicators can be estimated at early design in the case studied	Information detail increases across design stages; estimates remain dependent on available inputs
Onososen & Musonda (2022)	Interpretive structural modelling and MICMAC analysis of implementation barriers	Organises barriers involving model management, data quality, modelling errors and data exchange	Focuses on adoption barriers, not comparative structural carbon performance
Klumbyte et al. (2023)	API-based 6D BIM workflow using IFC, spreadsheets and EPD data	Demonstrates automated extraction and BIM-linked LCA outputs compared with commercial software	Material mapping and regional database availability remain important
Boje et al. (2023)	BIM and digital-twin framework tested on a real office building	Connects environmental, economic and social assessment with operational data	Data completeness and fragmented pipelines limit continuous LCSA
Pan et al. (2024)	Review of BIM–LCA integration and automation approaches	Classifies conventional, static and dynamic integration and discusses AI opportunities	Review-level evidence depends on scope and quality of included publications
Abdelaal et al. (2024)	BIM–LCA–AHP assessment of OPC, fly-ash and GGBFS concrete alternatives	Shows that supplementary cementitious materials can reduce case-study carbon and energy indicators	AHP weights and case-specific EPD/database assumptions affect the ranking
Soust-Verdaguer et al. (2024)	Smart BIM3LCA plug-in integrating LCSA and TOPSIS for early material selection	Automates multi-dimensional assessment and exposes weighting sensitivity	Composite rankings depend on selected indicators and weights
Yavan et al. (2024)	Dynamo, finite-element analysis, genetic algorithms and Revit for truss optimisation	Connects parametric structural optimisation with subsequent LCA and quantity analysis	Demonstration uses benchmark problems; project-specific validation remains necessary
Selfa et al. (2025)	BIM, FEA and three LCA tools applied to a Valencian barraca with three material scenarios	Directly compares traditional adobe/wood, concrete/steel and concrete/wood scenarios	Large differences between tool outputs and biogenic-carbon treatment complicate comparison
Parece et al. (2025)	Systematic review of 115 studies published during 2019–2024	Reports strong LCI automation but persistent manual mapping in LCIA and limited decision-support integration	Review identifies broad trends; percentages describe its selected corpus, not all BIM–LCA practice

4.1 Automation and interoperability

The studies show that BIM can make quantity extraction more repeatable, but a model object must still be mapped to the correct environmental record. Differences in material naming, classification, units, product specifications and geography can lead to mismatches. Klumbyte et al. (2023) demonstrate an API route that combines BIM-derived information with IFC, spreadsheet and EPD inputs. Pan et al. (2024) describe the evolution from spreadsheet exchange towards static and dynamic integration. More recent systematic evidence from Parece et al. (2025), based on 115 studies from 2019–2024, indicates that automation is stronger in the life-cycle inventory stage than in life-cycle impact assessment: the review reports 90% automation for LCI, while 77% of studies still relied on manual data mapping during LCIA. This gap is important because an automated quantity schedule can still produce unreliable results if the impact-factor mapping is incorrect.

4.2 Structural optimisation and material selection

Structural optimisation provides a route to reducing environmental impact without relying only on substitution of one material for another. Eleftheriadis et al. (2018) integrated BIM-based carbon assessment with multi-objective optimisation of reinforced-concrete structural alternatives, identifying trade-offs between cost and embodied carbon. Yavan et al. (2024) combined parametric truss generation, finite-element analysis and genetic algorithms, then

transferred the optimised model into Revit for further engineering analysis, including LCA and quantity surveying. These approaches emphasise that structural geometry, member sizing and material quantities should be considered together.

Material substitution can also produce substantial differences. Abdelaal et al. (2024) compared traditional concrete with mixes containing 30% fly ash and 50% ground-granulated blast-furnace slag (GGBFS) in a multi-storey car-park case. The reported embodied-carbon totals were 1,530.09, 1,271.48 and 962.03 t CO_2-eq, respectively, while embodied energy decreased from 4,469,668 MJ for ordinary Portland cement (OPC) concrete to 3,174,718 MJ for the 50% GGBFS alternative. The case study therefore supports the potential of supplementary cementitious materials, while also showing that material cost, availability, structural performance and local supply conditions must be considered.

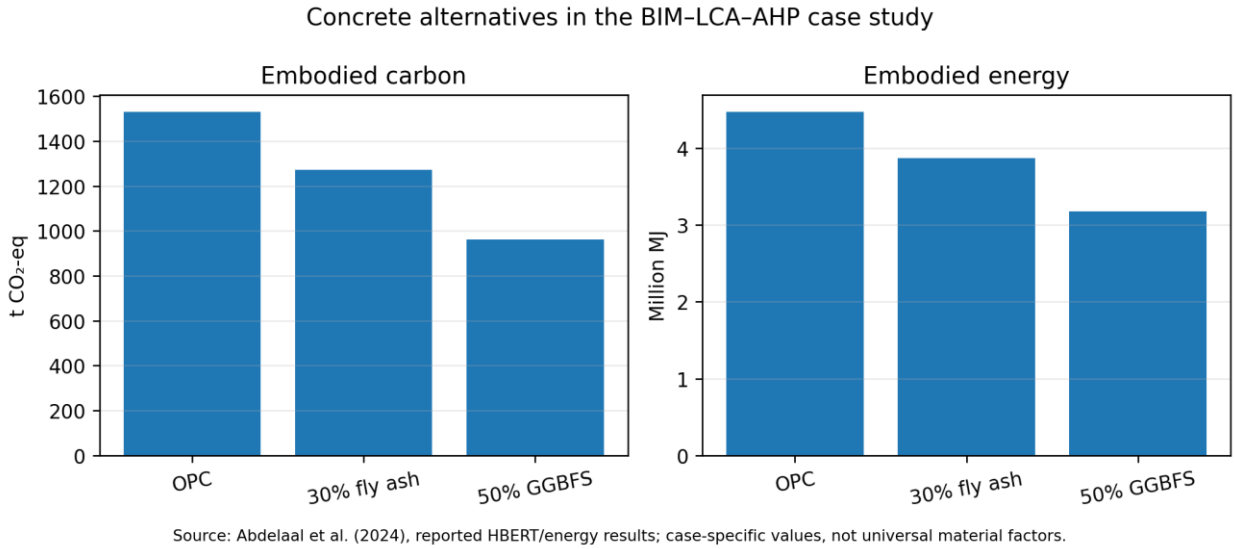


Figure 3. Case-study embodied carbon and energy for three concrete alternatives reported by Abdelaal et al. (2024). These are project totals from the investigated structure, not generic emission factors.

4.3 Tool sensitivity in structural material comparisons

The Valencian barraca study by Selfa et al. (2025) compares a traditional adobe-and-wood scenario, a concrete-and-steel scenario and a concrete-and-wood scenario. The reported A1–A3 GWP values vary substantially among Tally, Tekla Structural Designer and One Click LCA. The traditional scenario is lowest in each of the three tools, but the absolute values differ markedly. One Click LCA also treats biogenic carbon where available in EPDs, which affects the interpretation of timber-containing scenarios. The comparison is useful as an illustration of database and tool sensitivity; it is not appropriate to average the three tools or treat them as interchangeable measurements.

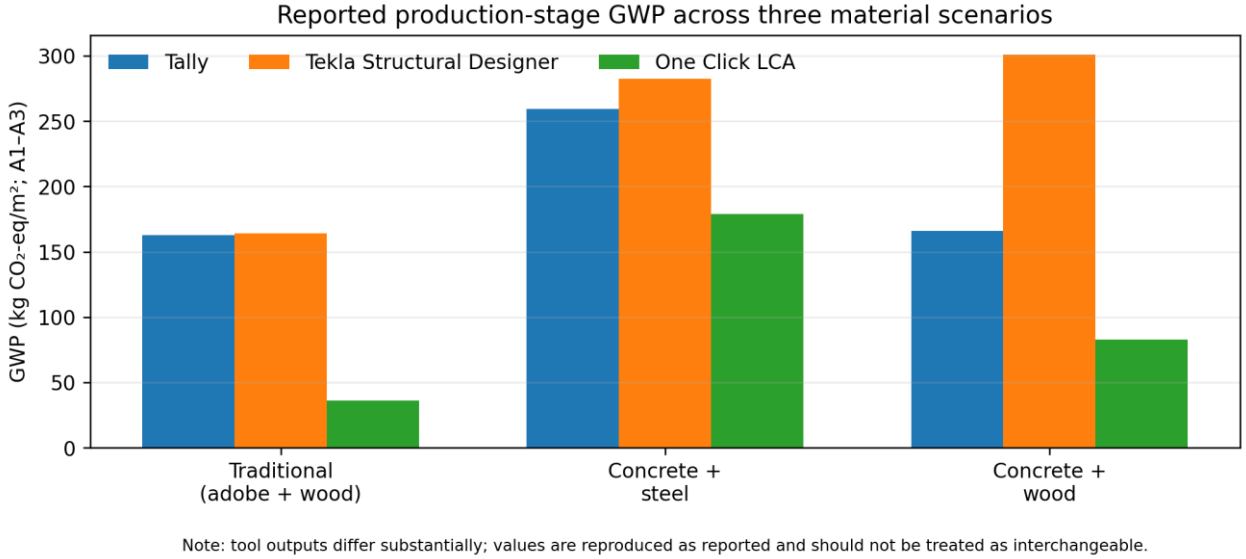


Figure 4. Production-stage GWP reported by Selfa et al. (2025) for three structural material scenarios. Values are shown separately by software because their datasets and assumptions differ.

4.4 Multi-criteria sustainability assessment

Environmental indicators do not fully represent sustainability. Life-cycle sustainability assessment can incorporate environmental, economic and social dimensions, but a composite ranking depends on indicator selection, normalisation and weighting. Soust-Verdaguer et al. (2022) proposed a BIM-based method to support consistent environmental, economic and social assessment across design stages. Their case study indicated that more than 60% of LCSA inventory indicators could be estimated during early design. Soust-Verdaguer et al. (2024) developed the Smart BIM3LCA plug-in, integrating LCSA with TOPSIS to support early material selection. Abdelaal et al. (2024) applied AHP to rank concrete alternatives using carbon, embodied energy and cost. These methods can structure trade-offs, but the final score should never replace disclosure of the underlying indicators and weights.

4.5 Digital twins and whole-life assessment

BIM models primarily describe design information, while digital twins can incorporate data from the building in operation. Boje et al. (2023) proposed and tested a BIM–digital-twin framework for life-cycle sustainability assessment of a real office building. Such a connection can help compare predicted and measured performance and improve estimates for operational stages. However, it requires reliable sensor data, consistent asset information, data governance and interoperability across the building life cycle. Digital twins should therefore be viewed as a developing extension to BIM–LCA rather than a substitute for robust LCA scope and inventory data.

5. Comparative quantitative evidence

5.1 Material-scenario comparison: Valencian barraca

Table 2 reproduces the A1–A3 GWP values reported by Selfa et al. (2025). The results are presented as a software-by-scenario matrix to make the spread visible. The same scenario does not yield the same numerical result in every tool; consequently, the figure is descriptive rather than a pooled comparison.

Structural scenario	**Tally**	**Tekla Structural Designer**	**One Click LCA**
Traditional (adobe + wood)	162.6	164.03	36
Concrete + steel	259.3	282.37	179
Concrete + wood	166.1	300.88	83

Unit: kg CO_2-eq/m², modules A1–A3. Source: Selfa et al. (2025). Tool-specific datasets, assumptions and biogenic-carbon treatment differ; direct averaging is not justified.

5.2 Concrete alternatives: carbon, energy and cost

Indicator	**OPC concrete**	**30% fly ash**	**50% GGBFS**
Embodied carbon (t CO_2-eq)	1,530.09	1,271.48	962.03
Embodied energy (MJ)	4,469,668	3,863,966	3,174,718
Total cost (Egyptian LE)	1,739,244	1,749,019	1,775,586

Source: Abdelaal et al. (2024). The 50% GGBFS case had the lowest reported embodied carbon and energy, while its reported total cost was higher than the OPC option. The cost values are specific to the study's Egyptian market assumptions and should not be transferred to another location or date without updating prices.

5.3 Interpretation of the numerical evidence

Across the two material case studies, lower-impact alternatives appear feasible, but the preferred option depends on the assessment framework. In the concrete study, the 50% GGBFS mixture reduced the reported total embodied carbon relative to OPC, while the cost estimate increased. In the barraca study, the traditional material scenario was lowest across the three reported tools, but the absolute GWP values varied considerably. Together, these examples show why a paper should report the functional unit, life-cycle modules, dataset geography, software version and treatment of biogenic carbon alongside every numerical comparison.

6. Discussion

The reviewed literature supports the use of BIM as a practical information backbone for life-cycle assessment, particularly when structural quantities are required repeatedly during design development. The value of integration is strongest when it closes the feedback loop between design changes and environmental assessment. Yet automation should not be confused with validity. A workflow may extract quantities automatically and still be inaccurate if structural components are missing, material records are incorrectly assigned or environmental datasets do not represent the actual supply chain.

A second finding is that structural sustainability is a multi-variable design problem. Optimising only the embodied carbon of one material can overlook changes in member sizes, reinforcement, foundations, construction methods, durability or operational performance. Structural alternatives should be compared on equivalent functional performance and assessed at an appropriate building-system level. This is consistent with the optimisation work of Eleftheriadis et al. (2018) and the truss workflow of Yavan et al. (2024).

A third finding concerns decision transparency. AHP and TOPSIS can make multi-criteria selection explicit, but their rankings are conditional on criteria and weights. A preferred option should therefore be accompanied by the raw environmental, economic and social indicators, the weighting procedure and sensitivity checks. This avoids presenting a single composite score as an objective universal answer.

Finally, the evidence points to a gap between technical demonstrations and routine practice. Ononosen and Musonda (2022) identify barriers associated with model management, data availability and quality, modelling errors, data exchange and manual workflows. Parece et al. (2025) likewise report persistent manual mapping during impact assessment and limited integration of multi-criteria decision analysis or multi-objective optimisation. These findings suggest that progress depends as much on standardised information management, skills and data governance as on software development.

7. Research gaps and future directions

Research gap	**Why it matters**	**Recommended direction**
BIM–LCA interoperability	Model objects and LCA datasets use different classifications, units and property structures	Develop tested IFC-based mappings, common property templates and traceable conversion rules
Regional LCI and EPD coverage	Imported datasets may not represent local manufacturing, electricity, transport or recycled content	Build verified regional datasets for concrete, steel, timber and alternative structural materials
LOD and uncertainty reporting	Early-stage models omit components and contain uncertain quantities	Report LOD/information requirements, exclusions, data quality and sensitivity ranges
Whole-life and circularity	Production-stage studies omit maintenance, replacement, demolition, reuse and recycling	Extend assessments across A–D modules and prevent double counting of recovery benefits
Structural functional equivalence	Material alternatives may not provide the same strength, service life or performance	Define functional units and verify structural safety, durability and serviceability before comparison
Decision-making transparency	AHP/TOPSIS rankings depend on weights and selected indicators	Publish weights, normalisation, raw indicators and sensitivity of rankings
Real-project validation	Many workflows are tested on limited case studies or benchmarks	Validate across building types, climates, regions and independently checked LCA calculations
Operational feedback	Design estimates may differ from actual operation	Connect BIM–LCA with digital-twin data and measured energy/water performance

7.1 Proposed research framework

Future work should combine structural design verification and environmental assessment in a single transparent process. A practical framework would begin with a defined functional unit and structural performance requirements; develop a BIM model with documented information requirements; map quantities to verified, geographically appropriate EPD/LCI records; assess consistent life-cycle modules; and compare alternatives using both individual impact indicators and clearly disclosed multi-criteria methods. Sensitivity analysis should test uncertain quantities, dataset choices and weighting factors. The final workflow should be validated against an independent LCA calculation and, where possible, operational data.

Prioritise open and auditable exchange rather than relying exclusively on closed software environments.

Treat structural performance, durability and constructability as constraints, not optional sustainability indicators.

Report environmental results separately before presenting any aggregated sustainability ranking.

Make data provenance, assumptions, exclusions and software versions reproducible.

8. Conclusions

This critical review examined selected research on BIM-enabled LCA for sustainable structural design. The literature demonstrates that BIM can provide geometry, material and quantity information that supports more iterative environmental assessment. API-based workflows, plug-ins, structural optimisation and digital-twin frameworks have expanded the ways in which environmental information can be incorporated into design decisions. Case studies also show that structural material choices and optimisation can materially influence reported embodied impacts.

The review also identifies important conditions for credible results. BIM-based quantity extraction does not by itself ensure a valid LCA; data mapping, environmental dataset quality, geographic relevance, functional equivalence, model detail and life-cycle boundaries remain decisive. Numerical outputs from different software platforms may differ substantially and should not be averaged without harmonised assumptions. Multi-criteria methods can broaden decision-making, but their rankings depend on disclosed indicators and weights.

The most important future priorities are interoperable BIM–LCA data structures, regional LCI and EPD datasets, consistent LOD and uncertainty reporting, broader whole-life and end-of-life assessment, transparent multi-criteria analysis and validation on real projects. BIM should therefore be understood as an enabling platform for life-cycle decision support. Its contribution to sustainable structural design depends on the quality, transparency and engineering validity of the assessment process built around it.

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