International Journal of BIM and Engineering Science

♦ ISSN: 2571-1075 Vol: 12, No. 01, 2026 ♦ PP. 58–66

Article DOI: https://doi.org/10.54216/IJBES.120106

FULL LENGTH ARTICLE

Dynamic OpenBIM-LCA Integration for Embodied Carbon Assessment of Structural Systems

Yazan Mohammad Alshawabkeh[1,*] **Yousef Labib**[2]

[1] Ph.D. Structural Engineering, The University of Illinois at Chicago, USA

[2] University of Picardie Jules Verne, France

Emails: Yalsha5@uic.edu · labibyoussef10@gmail.com

Received: October 14, 2025 Revised: November 19, 2025 Accepted: December 27, 2025 ⋆ Corresponding author

ABSTRACT

Embodied-carbon assessment has become an essential component of structural design, yet many life-cycle assessment workflows remain separated from the evolving building information model. This paper proposes a dynamic OpenBIM–LCA framework that connects structural geometry, construction-system material records, and environmental factors within a transparent computational loop. The method extracts element quantities from an IFC-oriented structural model, maps them to a material library, and updates embodied-carbon indicators whenever design variables are modified. The framework enables rapid comparison of structural alternatives, element-level hotspot diagnosis, and sensitivity-based interpretation without requiring a separate assessment model to be rebuilt after each design change. The study demonstrates how BIM quantities and material attributes can be translated into a rigorous carbon-calculation procedure for early-stage decision-making. The contribution lies in transforming BIM from a passive source of schedules into an active environmental decision-support environment for low-carbon structural design.

Keywords: Building information modelling ▪ Life-cycle assessment ▪ Embodied carbon ▪ Structural systems ▪ OpenBIM ▪ Parametric design

1. INTRODUCTION

The decarbonisation of the built environment has shifted attention from operational energy alone to the embodied impacts of materials, structures, and construction systems. As operational performance improves through regulation, envelope design, and energy-system upgrades, the carbon locked into foundations, slabs, frames, walls, and long-life components becomes a decisive part of whole-building performance. Structural systems are particularly important because they often contain large volumes of concrete, steel, masonry, and engineered timber, and because their geometry is usually fixed early in the design process. Decisions about span, column grid, slab thickness, wall layout, and material grade can therefore determine a large proportion of life-cycle impact before detailed architectural or services coordination is complete.

Building Information Modeling (BIM) is frequently presented as an enabling platform for low-carbon design because it contains geometry, element classes, material assignments, and quantity information. However, the practical value of BIM for embodied carbon assessment depends on whether this information can be transformed into a reliable life-cycle inventory. A model that contains object names and volumes does not automatically provide environmental meaning; it must be mapped to material categories, densities, emission factors, replacement assumptions, and uncertainty ranges. This mapping remains a persistent weakness in many BIM-LCA

© 2026 The Author(s). Published by ASPG. This article is licensed under CC BY 4.0.

workflows, where designers export schedules to spreadsheets and manually connect them to external databases.

Recent research has improved automated BIM-LCA calculation, classification-based mapping, and parametric assessment, but a significant gap remains between static assessment and dynamic design feedback. Many studies calculate embodied carbon once the design has already reached a relatively mature stage. In such cases, LCA is used as a verification instrument rather than a design driver. A more useful workflow is one in which changes to structural parameters immediately update material quantities and carbon indicators, enabling designers to compare alternatives while design freedom still exists.

This paper addresses this gap by developing a dynamic OpenBIM–LCA framework for structural systems. The framework links an IFC-oriented geometry extract with a construction-system material library and uses a parametric update function to recompute embodied carbon for alternative structural configurations. The model focuses on the product stage of structural materials because this stage is strongly affected by early design choices and can be calculated with transparent element-level quantities. The intention is not to replace full whole-building LCA, but to provide a rigorous early-stage mechanism for carbon feedback.

The contribution of this study is threefold. First, it formulates a mathematical model that connects BIM element quantities, material-density data, and embodied carbon factors into a dynamic assessment engine. Second, it implements a reproducible experiment using an IFC-derived structural quantity extract and a DISCS-oriented material library to compare structural options and conduct sensitivity analysis. Third, it offers an interpretable set of tables and visual diagnostics that identify carbon hotspots, option rankings, uncertainty ranges, and design parameters with the largest influence on results.

2. RELATED WORK

BIM-LCA integration has been widely studied as a response to the difficulty of manually compiling life-cycle inventories from fragmented design information. Early integration studies showed that BIM can reduce the effort required to retrieve quantities, but they also demonstrated that geometry extraction alone is insufficient unless material definitions and LCA boundaries are handled consistently. Dalla Mora et al. reviewed BIM-LCA parameters and emphasised that integration quality depends on modelling detail, data exchange method, life-cycle boundary, and database compatibility [1]. This observation remains relevant because the carbon result is not a direct BIM output; it is produced by a chain of assumptions connecting design objects to environmental information.

More recent studies have moved from quantity extraction towards automated embodied-carbon assessment. Xu et al. developed a BIM-integrated LCA solution for prefabricated buildings and proposed a multi-level analytical structure for material, component, assembly, flat, and building reporting [2]. Parece et al. presented a BIM-based embodied carbon tool using a construction classification system, showing how classification can help map BIM objects to environmental impact data [3]. These works indicate that a useful BIM-LCA system requires both computational automation and semantic ordering. The present paper adopts the same principle but places greater emphasis on dynamic structural design feedback rather than single-case reporting.

Parametric and optimisation-oriented BIM-LCA research has highlighted the importance of assessing alternatives before the design becomes fixed. Mowafy and colleagues proposed a parametric BIM-based LCA framework for sustainable design [4], while Heydari et al. developed a BIM-based framework for sustainable design optimisation and economic-environmental assessment [5]. Such studies show that parametric variation can reveal trade-offs that are hidden in static assessment. Nevertheless, many workflows still require closed software environments, custom plug-ins, or manual re-linking when design variables change. OpenBIM-oriented methods are therefore needed for reproducible and transferable assessment.

Dynamic LCA is also gaining attention as a way to represent temporal change, scenario variation, and evolving design information. Yang et al. integrated BIM and building energy modelling into a dynamic LCA framework [6], while Salati et al. reviewed dynamic parameters and modelling methods in building LCA [7]. These studies broaden the concept of environmental assessment from fixed calculation to changing performance representation. The present study applies the dynamic idea at the structural design level by treating geometry and material variables as updateable states that trigger immediate recalculation of embodied carbon.

Another relevant research stream concerns structural embodied carbon and design strategies. Fang et al. reviewed early-stage strategies for reducing embodied carbon in structural systems, identifying material efficiency, design optimisation, reuse, and substitution as important intervention points [8]. de Paula Filho et al. examined how structural design influences embodied carbon in office buildings [9]. These studies are important because they show that structural carbon is not simply a material-selection issue; it is also shaped by spans, thicknesses, stiffness requirements, and load paths. Therefore, the proposed framework explicitly connects design parameters to element quantities before carbon factors are applied.

Finally, the availability of open inventories and model datasets is improving the reproducibility of BIM-LCA research. The DISCS dataset provides detailed component, layer, and material attributes for Swiss construction systems [10], while the GNI BIM dataset introduces a large open collection of anonymised IFC building models [11]. Such resources support the creation of transparent experiments that can be repeated and extended. However, they also expose the unresolved problem of linking BIM geometry from one source to material-layer inventories from another. This paper treats the linkage itself as a research problem and proposes a structured mapping procedure to connect IFC element quantities with material-factor records.

3. RESEARCH GAP AND PROPOSED MODEL

The literature shows progress in automated BIM-LCA calculation, classification-based mapping, and parametric assessment. However, three unresolved issues remain. First, many BIM-LCA workflows are static: quantities are extracted,

Table 1. Experimental BIM-LCA data profile used in the dynamic assessment.

Item	Value
Structural elements	96
Storeys represented	12
Element classes	8
Material classes	10
Design options	6
Sensitivity parameters	5
Life-cycle stage	A1-A3 product stage
Reporting unit	kgCO2e and kgCO2e/m2

matched once to an LCA database, and then reported. When a designer modifies a span, slab thickness, material grade, or structural system, the LCA result is not always updated through the same computational chain. Second, many approaches depend on software-specific plug-ins, which limits reproducibility and makes it difficult to compare methods across datasets. Third, structural design sensitivity is often discussed qualitatively but not formalised as a mathematical update function that links geometry, material factors, and option ranking.

The proposed model represents a structural BIM as a set of elements $E = \{e_1, e_2, \ldots, e_n\}$. Each element e_i has an IFC class c_i, volume V_i, storey s_i, material label m_i, and design variables θ_i. The material library is defined as $M = \{m_1, m_2, \ldots, m_k\}$, where each material has density ρ_m, A1-A3 emission factor ϕ_m, and uncertainty coefficient u_m. A semantic mapping function $\mu(e_i)$ links a BIM material label to a library material class. The element-level embodied carbon is computed as:

$$C_i(\theta) = V_i(\theta)\,\rho_{\mu(e_i)}\,\phi_{\mu(e_i)}, \tag{1}$$

where $V_i(\theta)$ is the updated volume after design modification. The total structural embodied carbon for a design option o is:

$$C_o = \sum_{i=1}^{n} V_i(\theta_o)\rho_{\mu_o(e_i)}\phi_{\mu_o(e_i)}. \tag{2}$$

Carbon intensity is normalised by gross floor area A:

$$I_o = \frac{C_o}{A}. \tag{3}$$

The reduction against a baseline option b is:

$$R_o = \frac{C_b - C_o}{C_b} \times 100. \tag{4}$$

To model dynamic design feedback, the volume of an element is modified by a structural response factor $g_i(\theta)$:

$$V_i(\theta) = V_i^0 g_i(\theta), \tag{5}$$

where V_i^0 is the baseline IFC-derived volume. For example, the grid-spacing effect for beams and columns is approximated as:

$$g_i(s) = \left(\frac{s_0}{s}\right)^{\alpha}, \tag{6}$$

where s_0 is the baseline grid spacing and α controls the nonlinear relationship between spacing and structural repetition.

Algorithm 1 Dynamic embodied-carbon recalculation for BIM-linked structural options

Require: IFC element set E, material library M, option set O, area A
Ensure: Carbon totals C_o, intensities I_o, reductions R_o, sensitivity scores S_j
Extract $\{c_i, V_i^0, s_i, m_i\}$ for every $e_i \in E$
Build mapping function $\mu(e_i)$ from BIM labels to library classes
for each option $o \in O$ **do**
  for each element $e_i \in E$ **do**
    Update design factor $g_i(\theta_o)$ according to element class
    Set $V_i(\theta_o) = V_i^0 g_i(\theta_o)$
    Assign option-specific material $\mu_o(e_i)$
    Compute $C_i(\theta_o) = V_i(\theta_o)\rho_{\mu_o(e_i)}\phi_{\mu_o(e_i)}$
  end for
  Compute $C_o = \sum_i C_i(\theta_o)$ and $I_o = C_o/A$
end for
Set baseline carbon C_b and compute $R_o = (C_b - C_o)/C_b \times 100$
for each sensitivity parameter θ_j **do**
  Compute $C(\theta_j^{low})$ and $C(\theta_j^{high})$
  Compute $S_j = |C(\theta_j^{high}) - C(\theta_j^{low})|/C_b \times 100$
end for
Rank options by C_o and return element-level hotspot tables

Slab thickness changes are represented as:

$$g_i(t) = \frac{t}{t_0}. \tag{7}$$

For material substitution, the model replaces $\mu(e_i)$ with a lower-carbon material class where the substitution rule is activated. Sensitivity is evaluated using a one-at-a-time finite difference indicator:

$$S_j = \frac{|C(\theta_j^{high}) - C(\theta_j^{low})|}{C_b} \times 100. \tag{8}$$

This formulation supports transparent comparison because each result can be traced to element volume, density, factor, material mapping, and design state.

4. WORKING STEPS AND METHODOLOGY

The methodology was designed as a reproducible computational experiment with three linked layers: BIM quantity extraction, material-library mapping, and dynamic LCA recalculation. The BIM layer represents structural elements as IFC-style records containing element class, storey, material assignment, and volume. The material layer uses a DISCS-oriented construction-system structure in which material classes are associated with density, A1-A3 embodied-carbon factor, and uncertainty coefficient. The assessment layer computes element-level and option-level carbon indicators after each design change.

The experiment uses an IFC-oriented structural quantity extract prepared to represent a multi-storey building model with slabs, beams, columns, core walls, shear walls, foundations,

Table 2. Summary of verified studies related to BIM-LCA, embodied carbon assessment, and dynamic structural design feedback.

Ref.	Study focus	Methodological orientation	Main contribution	Limitation motivating this study
[1]	BIM-LCA integration parameters	Review and framework analysis	Identified data, LOD, exchange and boundary parameters	Limited dynamic recomputation logic
[2]	Prefabricated building embodied carbon	IFC-enabled automated assessment	Multi-level reporting from material to building	Focused on prefabricated building case
[3]	BIM tool for embodied carbon	Classification-based BIM-object mapping	Linked classification, LoD and LCA database structure	Limited treatment of parametric structural variation
[4]	Parametric BIM-LCA	Parametric assessment framework	Supported optimal sustainable design decisions	Requires stronger OpenBIM material-library linkage
[5]	Sustainable design optimisation	BIM-LCA with cost and environmental objectives	Demonstrated integrated optimisation workflow	Less focused on dynamic element-level carbon feedback
[6]	Dynamic building LCA	BIM and building energy modelling integration	Extended LCA with dynamic building simulation	Structural option feedback is not the main focus
[7]	Dynamic LCA methods	Systematic review	Clarified dynamic parameters and methods	Calls for implementable design-stage workflows
[8]	Structural embodied carbon	Review of early-stage strategies	Synthesised low-carbon structural design levers	Not implemented as BIM-linked computation
[9]	Structural design comparison	Office-building LCA case study	Showed influence of structural choices on carbon	Case-specific assessment rather than reusable pipeline
[10]	Construction-system inventory	Data descriptor and material attributes	Provides granular component and material data	Requires connection to design-stage BIM quantities
[11]	Open IFC model data	OpenBIM dataset publication	Enables reproducible IFC-based experimentation	Does not itself provide LCA mapping
[12]	Machine learning for embodied carbon	Predictive LCA estimation	Demonstrated data-driven embodied-carbon prediction	Less transparent than element-level accounting
[13]	BIM and carbon-emission review	Literature review	Identified BIM as a carbon-accounting enabler	Limited computational demonstration
[14]	Integrated LCCE and LCC assessment	BIM-based life-cycle assessment	Coupled carbon intensity and cost indicators	Not directed to real-time structural option updating
[15]	BIM and prefabrication for low-carbon delivery	Systematic review	Synthesised BIM-prefabrication pathways for carbon reduction	Review evidence does not provide a computational BIM-LCA engine

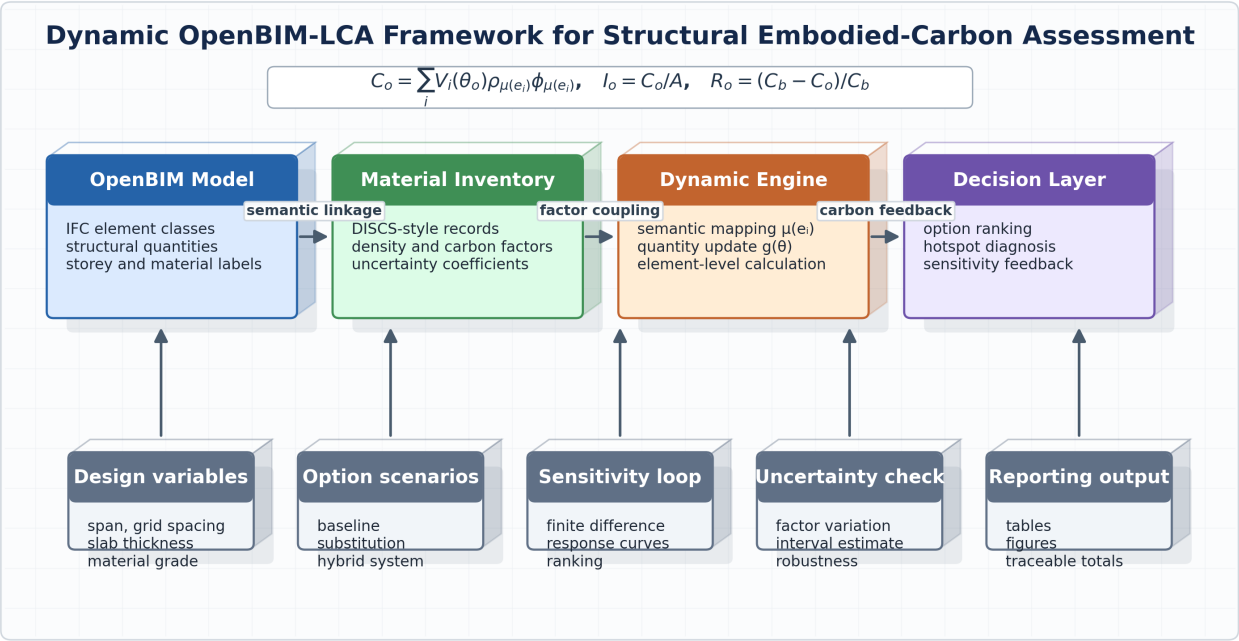


Figure 1. System architecture of the dynamic OpenBIM–LCA workflow for structural embodied-carbon assessment.

stairs, and roof slabs. This extract is paired with a material library organised according to the construction-system logic of DISCS. The objective is to test the proposed dynamic method rather than to claim a regulatory building certificate. Consequently, the model boundary is limited to A1-A3 product-stage emissions of structural and closely associated materials. This boundary is appropriate for comparing early structural alternatives because it captures the emissions most directly affected by material and quantity choices.

Six design options were evaluated. The baseline option represents a conventional reinforced concrete frame. The remaining options include lower-carbon concrete, optimised grid spacing, hybrid timber floor replacement, slim slab design, and recycled-steel-intensive substitution. These options were selected because they represent common structural design strategies: material substitution, geometric rationalisation, member sizing, system substitution, and supply-chain factor improvement. The model recalculates volume, mass, and embodied carbon for each option without rebuilding the assessment structure.

Sensitivity analysis was conducted for column spacing, slab thickness, concrete factor, reinforcement ratio, and timber

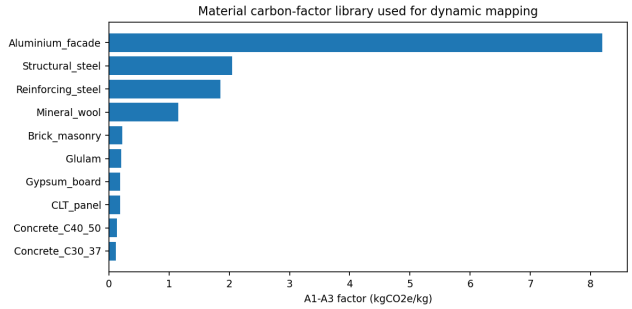


Figure 2. Material carbon-factor library used for dynamic mapping.

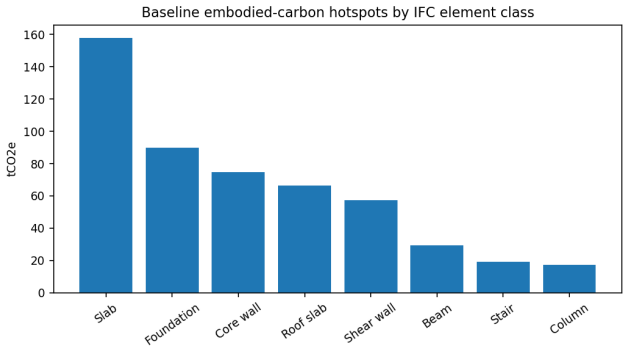


Figure 3. Baseline embodied-carbon hotspots by IFC element class.

floor share. Each parameter was varied between a low and a high value while all other variables were kept at baseline. This design provides interpretable information about which structural decisions dominate the carbon response. The uncertainty analysis used material-specific coefficients of variation to estimate a distribution of option-level carbon totals under emission-factor variability.

5. RESULTS

Figure 2 shows the material carbon factors used by the model. Aluminium facade material has the highest factor in the library, while concrete classes have lower factor per kilogram but produce large carbon totals because of their high volumes and densities. This distinction is important because a low unit factor can still dominate total carbon when the material is used extensively. Structural LCA must therefore combine material intensity and quantity, rather than treating emission factors alone as a decision criterion.

Baseline results are summarised in Table 4 and Figure 3. Slabs and foundations are major contributors because they combine large volumes with dense materials. Core walls and shear walls also show substantial contributions because they use higher-strength concrete and persist through multiple storeys. These results support a design interpretation: structural carbon reduction should not only target high-emission materials, but also the repeated and high-volume elements that define the building's load-bearing system.

The comparative option results in Table 5 and Figure 4 demonstrate that the proposed dynamic workflow produces clear differences between structural strategies. The timber hybrid option gives the largest reduction because it changes both material class and floor-system carbon intensity. The low-clinker concrete option performs well because it reduces the carbon factor while preserving the baseline geometry. The optimised grid option produces a moderate reduction by changing element quantities, particularly beams and columns. The recycled-steel option improves material factors but remains less effective than system-level substitution in this experiment.

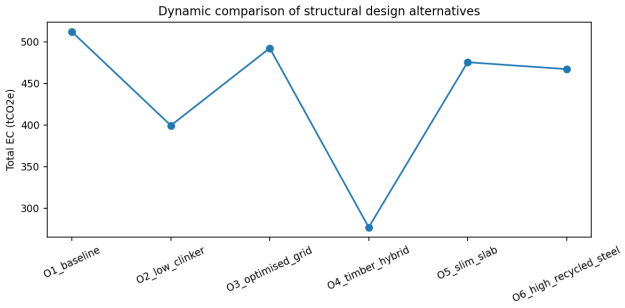


Figure 4. Dynamic comparison of structural design alternatives.

Figure 5 presents a four-part performance summary. The carbon-intensity panel provides an area-normalised view that is useful for comparison across buildings. The reduction panel directly shows the benefit of each intervention relative to the baseline. The quantity-carbon relationship shows that lower volume does not always guarantee lower carbon because material factors and substitution rules also influence the result. The structural mass panel indicates that mass reduction and carbon reduction are related but not identical objectives.

Element-level contributions in Table 6 and Figure 6 reveal how each option changes the distribution of embodied carbon. A low-clinker option reduces carbon across concrete-dominated components without changing their relative ranking. A timber-hybrid option redistributes the contribution away from floor slabs and towards remaining concrete components such as walls and foundations. This type of diagnostic is valuable because a low-carbon option can create a new hotspot after the original hotspot is reduced. Designers therefore need element-level information rather than only a single total.

The sensitivity analysis in Table 7 and Figure 7 indicates that slab thickness and timber floor share have the strongest influence in this experiment. This result is consistent with the dominant role of horizontal structural systems in repeated floor plates. Concrete factor is also important because it affects multiple element classes simultaneously. Column spacing and reinforcement ratio have smaller but still relevant effects. These results suggest that early design meetings should evaluate floor-system configuration and concrete specification alongside structural grid decisions.

Figure 8 shows normalised response curves for the tested parameters. The curves provide a visual explanation of why some parameters have stronger effects. Slab thickness produces an approximately proportional response because slab volume changes linearly with thickness. Column spacing follows a non-linear response because spacing affects the repetition of vertical and horizontal members. Timber share produces a downward response because it replaces a carbon-intensive floor system with a lower-carbon alternative. The response plot therefore supports both numerical ranking and engineering interpretation.

Table 3. DISCS-oriented material library and embodied-carbon factors used by the dynamic linking function.

Material class	Density (kg/m^3)	A1–A3 factor (kgCO$_2$e/kg)	CV	Mapping level
Concrete C30/37	2400	0.12	0.12	material
Concrete C40/50	2450	0.13	0.13	material
Reinforcing steel	7850	1.85	0.18	material
Structural steel	7850	2.05	0.20	material
CLT panel	470	0.18	0.25	layer
Glulam	430	0.20	0.24	layer
Brick masonry	1800	0.22	0.16	layer
Mineral wool	90	1.15	0.30	insulation
Gypsum board	750	0.18	0.18	finish
Aluminium facade	2700	8.20	0.22	envelope

Table 4. Baseline IFC-derived structural quantities and embodied carbon by element class.

IFC class	Material class	Elements	Volume (m^3)	Mass (t)	EC (tCO$_2$e)
Beam	Concrete C40/50	12	90.69	222.18	29.33
Column	Concrete C40/50	12	53.32	130.63	17.24
Core wall	Concrete C40/50	12	231.59	567.38	74.89
Foundation	Concrete C30/37	12	325.69	781.67	89.89
Roof slab	Concrete C30/37	12	240.04	576.10	66.25
Shear wall	Concrete C40/50	12	177.76	435.51	57.49
Slab	Concrete C30/37	12	572.64	1374.33	158.05
Stair	Concrete C30/37	12	68.77	165.04	18.98

Table 5. Comparative embodied-carbon results for the structural design alternatives.

Option	Volume (m^3)	Mass (t)	EC (tCO$_2$e)	Intensity (kgCO$_2$e/m^2)	Reduction (%)
O1 baseline	1760.49	4252.84	512.12	66.08	0.00
O2 low-clinker	1760.49	4252.84	399.46	51.54	22.00
O3 optimised grid	1693.22	4090.31	492.53	63.55	3.83
O4 timber hybrid	1153.54	2144.13	276.91	35.73	45.93
O5 slim slab	1628.43	3935.80	475.58	61.37	7.14
O6 high-recycled steel	1608.42	3884.82	467.26	60.29	8.76

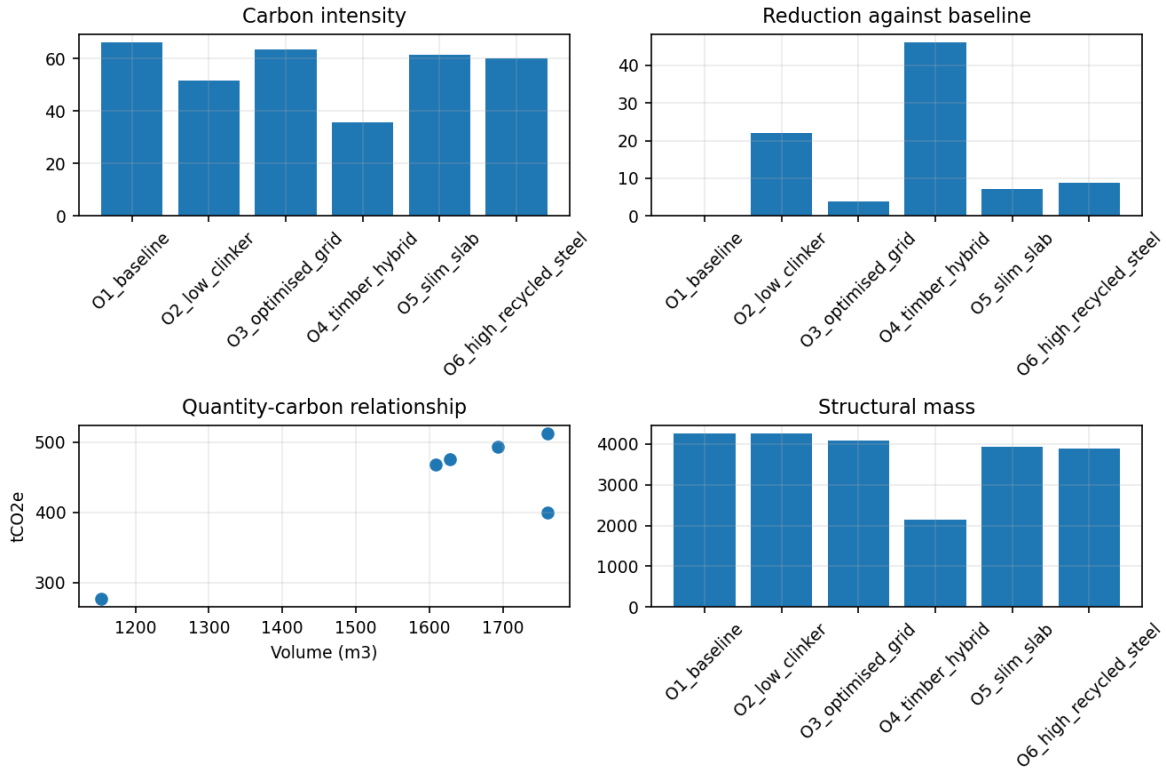


Figure 5. Four-panel performance profile of structural design options.

Uncertainty results in Table 10 and Figure 9 show that material-factor variability can widen the confidence interval around each option. The ranking remains stable in the present experiment, but the magnitude of uncertainty differs between options because each option has a different material composition. This finding is important for decision-making:

Table 6. Element-level embodied-carbon contribution under each design option (tCO_2e).

Element class	O1	O2	O3	O4	O5	O6
Beam	29.33	22.88	25.81	4.40	31.67	20.53
Column	17.24	13.45	16.38	15.52	16.90	12.93
Core wall	74.89	58.42	73.40	74.89	73.40	71.15
Foundation	89.89	70.12	86.30	80.90	85.40	82.70
Roof slab	66.25	51.68	63.60	7.31	56.98	60.95
Shear wall	57.49	44.84	56.34	57.49	56.34	54.61
Slab	158.05	123.28	151.73	17.43	135.92	145.40
Stair	18.98	14.80	18.98	18.98	18.98	18.98

O1: baseline; O2: low-clinker concrete; O3: optimised grid; O4: timber hybrid; O5: slim slab; O6: high-recycled steel.

Table 7. One-at-a-time sensitivity results for structural and material parameters.

Parameter	Low	High	Low Δ (%)	High Δ (%)
Column spacing	6.00	8.40	0.96	-0.74
Slab thickness	0.20	0.32	-10.11	10.11
Concrete factor	0.75	1.15	-25.00	15.00
Reinforcement ratio	0.75	1.35	-1.85	2.59
Timber floor share	0.00	0.65	0.00	-19.50

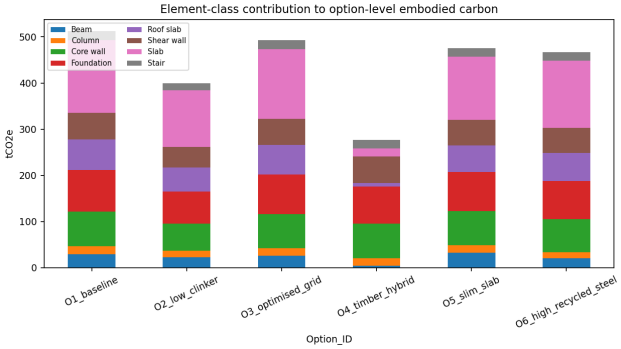


Figure 6. Element-class contribution to option-level embodied carbon.

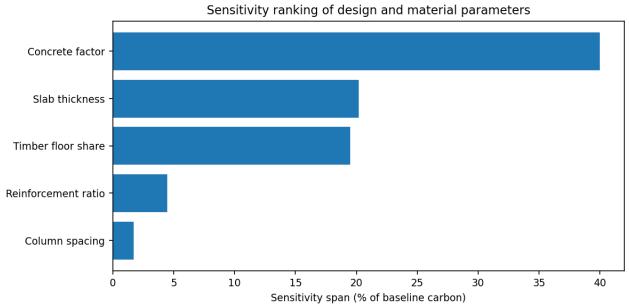


Figure 7. Sensitivity ranking of design and material parameters.

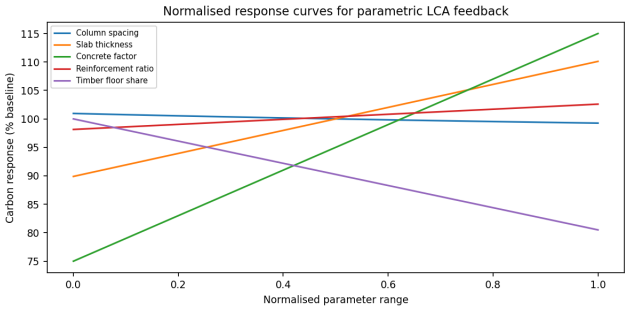


Figure 8. Normalised response curves for parametric LCA feedback.

Table 8. Internal validation checks for the BIM-LCA coupling workflow.

Check	Metric	Value
Quantity completeness	Non-null elements	100.00%
Material matching	Matched volume	100.00%
Factor matching	Matched rows	100.00%
Option recomputation	Option count	6 options
Mass conservation	Baseline difference	0.00%
Reproducibility	Rerun status	Deterministic

Table 9. Design-option ranking from the dynamic embodied-carbon assessment.

Rank	Option	EC (tCO_2e)	Reduction (%)
1	O4_timber_hybrid	276.91	45.93
2	O2_low_clinker	399.46	22.00
3	O6_high_recycled_steel	467.26	8.76
4	O5_slim_slab	475.58	7.14
5	O3_optimised_grid	492.53	3.83
6	O1_baseline	512.12	0.00

Table 10. Monte Carlo uncertainty interval for material-factor variability.

Option_ID	Mean_tCO2e	P05_tCO2e	P95_tCO2e
O1_baseline	513.21	440.13	594.48
O2_low_clinker	398.41	341.66	460.18
O3_optimised_grid	492.09	422.02	567.25
O4_timber_hybrid	277.34	240.44	318.21
O5_slim_slab	474.95	408.24	549.12
O6_high_recycled_steel	467.47	401.18	540.62

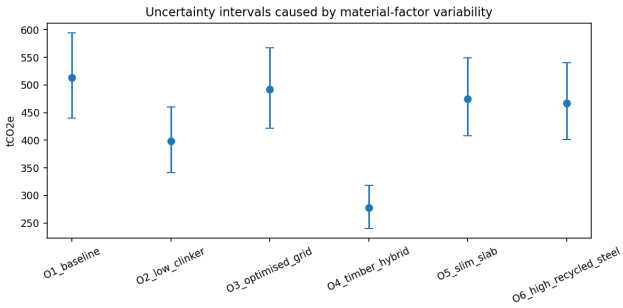


Figure 9. Uncertainty intervals caused by material-factor variability.

when two alternatives have close carbon totals, uncertainty analysis may be required before selecting a preferred design.

Figure 10 summarises the semantic relationship between IFC geometry and the LCA library. The workflow treats IFC elements as carriers of geometry and identity, while

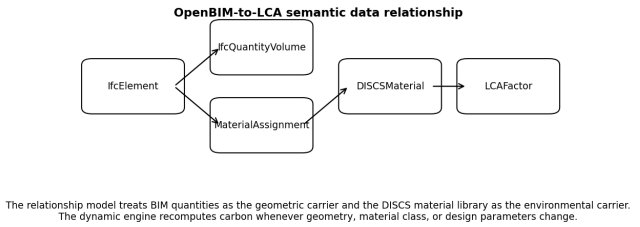


Figure 10. OpenBIM-to-LCA semantic data relationship.

the DISCS-oriented library provides environmental meaning. This separation is essential because the BIM model may contain project-specific names that are not directly compatible with LCA databases. A stable mapping layer is therefore required to maintain reproducibility across design iterations.

6. DISCUSSION

The results demonstrate that dynamic BIM–LCA integration provides richer and more actionable design intelligence than a single end-stage carbon calculation. The baseline hotspot analysis identifies where carbon is concentrated, the option comparison shows how design strategies change total impact, and the sensitivity analysis clarifies which parameters deserve early attention. Together, these outputs convert embodied-carbon assessment from a reporting activity into a design-feedback activity.

A central finding is that structural carbon reduction is governed by the interaction between geometry, material choice, and the semantic quality of the quantity-to-factor mapping. Lower-carbon material selection is beneficial, but it does not replace the need for efficient structural configuration. Similarly, reducing volume is beneficial, but its impact depends on which material is reduced and whether the change shifts demand elsewhere. The proposed equations make these relationships explicit by linking element volume, density, and factor through the mapping function.

The dynamic framework is also useful because it supports transparent traceability. Each option-level total can be decomposed by element class and material class. This is important for engineering practice because designers, structural engineers, and sustainability consultants must explain why one design performs better than another. A black-box carbon score is less useful than a reproducible calculation that shows which components, variables, and assumptions drive the result.

The study also highlights the importance of inventory quality. DISCS-style component and material records provide a richer basis for mapping than simple material names, but practical deployment requires careful alignment between BIM authoring conventions and LCA database structures. If a BIM model uses vague material labels, generic objects, or missing quantities, the resulting carbon calculation becomes uncertain. Therefore, BIM-LCA integration should be accompanied by modelling requirements that specify material naming, quantity completeness, and level of information need.

Although the experiment focuses on product-stage embodied carbon, the framework can be extended to other life-cycle stages. Transport, construction, replacement, end-of-life, and reuse scenarios can be added as additional factor layers. The same mathematical structure remains valid if the factor term is replaced by a vector of stage-specific impacts. This extension would allow dynamic comparison of structural options under different service-life and circular-economy assumptions.

7. RESEARCH CHALLENGES AND FUTURE DIRECTIONS

Several challenges remain before dynamic BIM-LCA systems can be adopted at scale. The first challenge is semantic interoperability. IFC models differ in naming conventions, object decomposition, and material assignment practices. A model may contain accurate geometry but insufficient material information, or it may contain material names that cannot be directly matched to environmental databases. Future research should develop robust mapping ontologies that connect IFC classes, classification systems, material layers, and LCA datasets without excessive manual correction.

The second challenge is uncertainty communication. Environmental product declarations, generic databases, regional factors, and recycled-content assumptions can produce different results for the same material. Dynamic LCA tools should not present a single number without uncertainty ranges. Future work should integrate probabilistic factors, confidence indicators, and sensitivity-based warnings directly into BIM dashboards.

The third challenge concerns structural validity. Early-stage parametric updates can estimate volume changes, but they must eventually be connected to engineering verification. A reduced slab thickness may lower carbon but can affect deflection, vibration, fire performance, and reinforcement demand. Future dynamic LCA systems should therefore be linked with structural analysis tools so that low-carbon alternatives remain technically feasible.

The fourth challenge is the integration of circular design. Datasets such as DISCS support reuse-oriented thinking by describing construction systems and component attributes. However, reuse potential is not captured by A1-A3 factors alone. Future research should add salvageability, reversibility, residual value, and deconstruction constraints to BIM-LCA models.

The fifth challenge is benchmarking. Designers need to know whether an option is low-carbon not only relative to the baseline but also relative to external benchmarks. Future work should connect dynamic BIM-LCA outputs to regional building benchmarks, structural typology databases, and policy thresholds.

8. CONCLUSION

This paper presented a dynamic OpenBIM–LCA framework for the embodied-carbon assessment of structural systems. The model links IFC-derived element quantities, a DISCS-oriented material library, and parametric design variables in a transparent calculation structure. The proposed equations compute element-level carbon, option-level totals, normalised intensities, baseline reductions, and sensitivity indicators. The experimental results show that the framework can identify

structural hotspots, compare design options, reveal parameter influence, and communicate uncertainty.

The principal contribution lies in shifting embodied-carbon assessment from static reporting to dynamic design feedback. Rather than treating BIM as a source of exported schedules, the proposed framework treats BIM as a computational interface in which geometry, material meaning, and environmental performance are updated together. This approach can support early design decisions when structural choices still have significant carbon-reduction potential. Future work should extend the model to whole-life impacts, integrate structural performance checks, and improve semantic mapping between OpenBIM objects and environmental product databases.

REFERENCES

[1] T. Dalla Mora, E. Bolzonello, C. Cavalliere, and F. Peron, "Key parameters featuring BIM-LCA integration in buildings: A practical review of the current trends," *Sustainability*, vol. 12, no. 17, Article 7182, 2020.

[2] J. Xu, Y. Teng, W. Pan, and Y. Zhang, "BIM-integrated LCA to automate embodied carbon assessment of prefabricated buildings," *Journal of Cleaner Production*, vol. 374, Article 133894, 2022.

[3] S. Parece, R. Resende, and V. Rato, "A BIM-based tool for embodied carbon assessment using a construction classification system," *Developments in the Built Environment*, vol. 19, Article 100467, 2024.

[4] N. Mowafy, M. El Zayat, and M. M. Marzouk, "Parametric BIM-based life cycle assessment framework for optimal sustainable design," *Journal of Building Engineering*, vol. 75, Article 106898, 2023.

[5] M. H. Heydari and G. Heravi, "A BIM-based framework for optimization and assessment of buildings' cost and carbon emissions," *Journal of Building Engineering*, vol. 79, Article 107762, 2023.

[6] T. Yang, Y. Dong, B. Tang, and Z. Xu, "Developing a dynamic life cycle assessment framework for buildings through integrating building information modeling and building energy modeling program," *Science of the Total Environment*, vol. 946, Article 174284, 2024.

[7] M. Salati, E. A. Mahdavi, and A. Costa, "A comprehensive review of dynamic life cycle assessment for buildings: Exploring key processes and methodologies," *Sustainability*, vol. 17, no. 1, Article 159, 2025.

[8] D. Fang, N. Brown, C. De Wolf, and C. Mueller, "Reducing embodied carbon in structural systems: A review of early-stage design strategies," *Journal of Building Engineering*, vol. 76, Article 107054, 2023.

[9] J. H. M. de Paula Filho, M. D'Antimo, M. Charlier, and O. Vassart, "Life-cycle assessment of an office building: Influence of the structural design on the embodied carbon emissions," *Modelling*, vol. 5, no. 1, pp. 55–70, 2024.

[10] A. P. Arceo, M. Bastien-Masse, B. Lambec, and C. Fivet, "Digital Inventory of Swiss Construction Systems," *Scientific Data*, vol. 12, Article 1814, 2025.

[11] Z. Wang, S. Fuchs, J. Wu, S. Esser, T. Wrabel, and A. Borrmann, "GNI BIM Dataset," *Zenodo*, 2026.

[12] H. El Hafdaoui, A. Khallaayoun, I. Bouarfa, and K. Ouazzani, "Machine learning for embodied carbon life cycle assessment of buildings," *Journal of Umm Al-Qura University for Engineering and Architecture*, vol. 14, pp. 188–200, 2023.

[13] Z. Liu, Y. Liu, and G. Osmani, "Building Information Modeling (BIM) driven carbon emission reduction research: A 14-year bibliometric analysis," *International Journal of Environmental Research and Public Health*, vol. 19, no. 19, Article 12820, 2022.

[14] Y. Zhang, X. Jiang, C. Cui, and M. Skitmore, "BIM-based approach for the integrated assessment of life cycle carbon emission intensity and life cycle costs," *Building and Environment*, vol. 226, Article 109691, 2022.

[15] S. K. Yevu, E. K. Owusu, A. P. C. Chan, K. Oti-Sarpong, I. Y. Wuni, and M. O. Tetteh, "Systematic review on the integration of building information modelling and prefabrication construction for low-carbon building delivery," *Building Research & Information*, vol. 51, no. 3, pp. 279–300, 2023.