Proceedings of the 4th International Conference on Functional Materials and Civil Engineering
DOI: 10.54254/2755-2721/2026.38358

Embodied Carbon Reduction Performance in the Adaptive Reuse of Existing Public Buildings: A BIM-Based Life Cycle Assessment Framework

Guoyu Ma

College of Art and Design, Chung-Ang University, Seoul, Republic of Korea
wellington589125@gmail.com

Abstract. Adaptive reuse can preserve carbon-intensive building components while avoiding material production associated with demolition and reconstruction, but its carbon benefit depends on structural retention, retrofit intensity, and future replacement cycles. This study develops a BIM-based life cycle assessment framework for 20 existing public buildings evaluated under adaptive-reuse and demolition-and-reconstruction scenarios. Autodesk Revit 2025 and Dynamo 3.2 are used to construct element-level material inventories, and openLCA 2.4 with ecoinvent 3.10 quantifies emissions across A1–A5, B4, and C1–C4 over 50 years. Illustrative analytical results show that adaptive reuse decreases embodied carbon from 842.3 ± 78.6 to 470.0 ± 61.4 kg CO_2e/m^2, giving a mean saving of 44.1 ± 5.8%. Structural retention contributes 59.8 ± 7.1% of avoided emissions and is the strongest predictor of carbon saving performance ($\beta = 0.671 \pm 0.112$, $p < 0.001$). Monte Carlo analysis produces a median saving rate of 42.8% with a 95% uncertainty interval of 31.6–53.7%. The framework provides a reproducible basis for carbon-informed public-building renewal decisions.

Keywords: adaptive reuse, embodied carbon, building information modeling, life cycle assessment, structural retention

1. Introduction

Increasingly, decarbonizing the building sector means considering embedded emissions in the material stocks of existing structures. Public buildings constructed several decades ago incorporate large amounts of reinforced concrete, steel, masonry, aluminum, glass, and finishes whose production already bears significant environmental impacts. Premature demolition loses any residual value from these components and increases demand for replacement materials. Adaptive reuse thus becomes a useful climate mitigation approach through extending building life cycles and decreasing demolition and new construction [1]. Existing building components may also be understood as environmental assets whose continued use bears embodied-energy value [2].

There is empirical evidence that repurposing non-residential buildings leads to lower life cycle energy consumption and greenhouse gas emissions compared to equivalent new constructions [3], and there are case-study LCA investigations that show how preservation of existing structural and

© 2026 The Authors. This is an open access article distributed under the terms of the Creative Commons Attribution License 4.0 (https://creativecommons.org/licenses/by/4.0/).

DOI: 10.54254/2755-2721/2026.38358

envelope elements improves environmental performance [4]. However, LCA for renovation is still methodologically inconsistent, as different functional units, system boundaries, replacement assumptions, and service lives are used in these studies [5]. This reduces comparability of carbon reduction claims and makes their use in public sector renewal policy difficult [6].

BIM may partially solve this issue by identifying retained, demolished, replaced, and newly installed components, and linking geometrical data to material amounts. There are recent BIM-LCA works that develop methods of BIM and LCA integration [7], highlight existing interoperability and information granularity issues [8], and propose more robust methods of calculating embodied impacts [9]. Application of BIM to adaptive reuse demonstrates its value in distinction between existing and new construction parts [10]. However, there is little comparative evidence about life cycle impacts of existing public buildings analyzed on the basis of identical functional, temporal, and structural assumptions. A replicable workflow that will enable to identify retained components and calculate carbon savings from their use, along with the effect of renovation intensity and parameters uncertainty, is needed. The current work develops a standard BIM-based LCA framework for evaluation of embodied-carbon savings, contributions of particular components, structural preservation effects, building type differences, and parameters uncertainty in existing public buildings.

2. Literature review

2.1. Embodied carbon in existing building renewal

Embodied carbon includes greenhouse-gas emissions from material extraction, manufacturing, transport, construction, replacement, demolition, waste processing, and disposal. Assessment is more complex for existing buildings because much of the material stock has already been produced and may remain technically functional. Renewal therefore determines whether the remaining service value of that stock is preserved or discarded [1-4]. Reinforced-concrete frames are especially influential because concrete and reinforcement occur in high masses and are difficult to replace without substantial new emissions. Carbon accounting must consequently distinguish retained, removed, replacement, and newly introduced materials rather than treat renovation as a reduced form of new construction.

2.2. Adaptive reuse as a carbon reduction measure

Adaptive reuse reduces demand for new materials by extending the functional lifetime of existing components. Its carbon advantage depends on both the quantity and carbon intensity of retained material. Preserving foundations, columns, beams, slabs, and envelope sections avoids production emissions for equivalent replacement components and reduces demolition burdens. However, intensive façade renewal, spatial reconfiguration, strengthening, and repeated replacement of interiors or services can offset part of this benefit. Carbon performance therefore reflects the balance between preserved material value and new life-cycle burdens [5-7].

2.3. BIM-based life cycle carbon assessment

The BIM integrates the geometry, type of material, quantities, and environmental properties of the components in a structured digital format. Classification of elements is important for adaptive re-use because the retained and removed materials are subject to different life cycle processes. Extraction

DOI: 10.54254/2755-2721/2026.38358

minimizes error due to manual data transfer, although consistency in naming, density, units, life cycle process, and database correlation is important for successful extraction [8-10]. Level of Detail 300 is adequate for component-based embodied carbon calculation.

3. Methodology

3.1. Case selection and BIM-based material inventory

Twenty reinforced-concrete public buildings are examined, with five cases each representing educational, administrative, cultural, and community-service functions. Eligibility requires at least 25 years of service, available architectural and structural drawings, and sufficient records to reconstruct principal material inventories. Gross floor area, structural system, façade type, retrofit history, and component condition are recorded before calculation. Each building is reconstructed to LOD 300 in Autodesk Revit 2025. Foundations, columns, beams, slabs, roofs, external walls, glazing, partitions, ceilings, floor finishes, and major service-related elements are modeled separately. Material properties contain a standardized code, density, life-cycle mapping identifier, and intervention status. A Dynamo 3.2 script extracts element IDs, volume, area, count, and material assignment. Mass is calculated from modeled volume and verified density. Elements are classified as retained, replaced, newly added, or demolished. Partially retained assemblies are decomposed at material level. CSV outputs are checked against drawing schedules and available bills of quantities; discrepancies above 5% trigger model correction. The overall methodological workflow integrates BIM-based material inventory, scenario-based life cycle assessment, carbon performance evaluation, and uncertainty analysis, as illustrated in Figure 1.

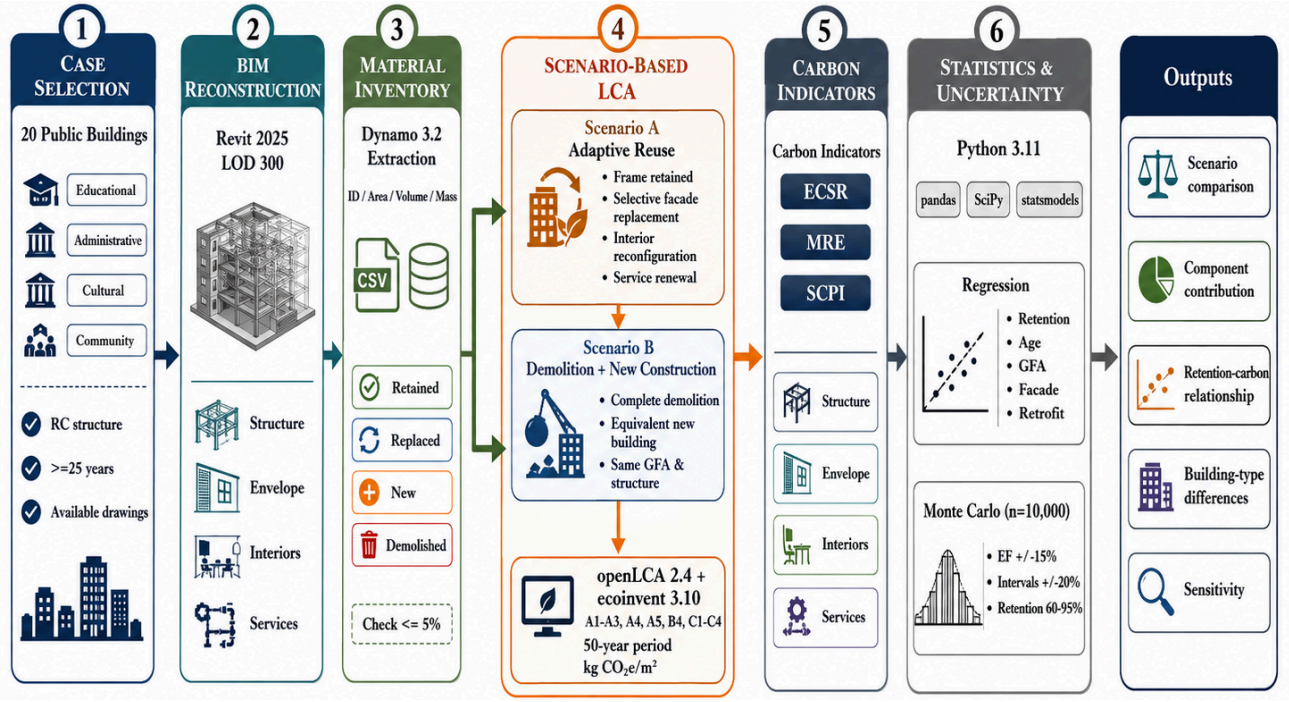

Figure 1. BIM-based life cycle assessment framework for evaluating embodied carbon reduction in adaptive reuse of existing public buildings

DOI: 10.54254/2755-2721/2026.38358

3.2. Life cycle assessment and reuse scenarios

Two standardized scenarios are generated. Scenario A represents adaptive reuse, retaining serviceable foundations and primary frames while selectively replacing damaged façade elements, reconfiguring interiors, renewing finishes, and replacing principal services. Scenario B assumes complete demolition followed by a functionally equivalent reinforced-concrete building with the same gross floor area and structural system.

Environmental calculations are performed in openLCA 2.4 using ecoinvent 3.10. The boundary covers A1–A3, A4, A5, B4, and C1–C4 over 50 years. Component service lives determine replacement cycles, while retained structural elements remain credited for continued service. Global warming potential is reported as kg CO_2e/m².

The embodied-carbon saving ratio is defined as shown in Equation (1):

$$ECSR = 100[1 - \frac{\sum_{i=1}^{N}[q_i(1-r_i)(e_{i,A1-A3}+d_i e_{i,A4}+c_i e_{i,A5}))}{\sum_{i=1}^{N}[q_i(e_{i,A1-A3}+d_i e_{i,A4}+c_i e_{i,A5}))} \tag{1}$$

$$+\sum_{k=1}^{\lfloor T/L_i \rfloor} q_i \rho_i e_{i,B4} + q_i \delta_i e_{i,C1-C4}]_{\mathrm{AR}}$$
$$+\sum_{k=1}^{\lfloor T/L_i \rfloor} q_i \rho_i e_{i,B4} + q_i \delta_i e_{i,C1-C4}]_{\mathrm{NC}}]$$

where q_i is material quantity, r_i is the retained fraction, e is stage-specific emission intensity, d_i and c_i are transport and construction coefficients, ρ_i is replacement quantity, δ_i is the end-of-life fraction, and AR and NC denote adaptive reuse and new construction.

3.3. Carbon performance indicators and sensitivity analysis

Embodied Carbon Saving Ratio measures total reduction relative to Scenario B. Material Retention Efficiency expresses avoided kg CO_2e per tonne retained, while Structural Carbon Preservation Index measures the share of baseline structural embodied carbon remaining in use. Avoided emissions are decomposed into structure, envelope, interiors, and services.

Analysis is conducted in Python 3.11 with pandas, SciPy, and statsmodels. Paired tests compare scenarios, while multiple linear regression models ECSR using structural retention rate, building age, log-transformed gross floor area, façade replacement ratio, and retrofit intensity. Variance inflation factors below 5 are required and heteroscedasticity-consistent standard errors are applied. Uncertainty is propagated through 10,000 Monte Carlo iterations using Latin hypercube sampling. Material emission factors vary by ±15%, replacement intervals by ±20%, and structural retention between 60% and 95%. Partial rank correlation coefficients identify influential inputs.

4. Results

4.1. Embodied carbon differences between adaptive reuse and new construction

Across the 20 illustrative cases, adaptive reuse produces 470.0 ± 61.4 kg CO_2e/m² versus 842.3 ± 78.6 kg CO_2e/m² for new construction. The paired difference is 372.3 ± 54.7 kg CO_2e/m², corresponding to an ECSR of 44.1 ± 5.8% ($t = 30.44$, $p < 0.001$) (see Table 1).

DOI: 10.54254/2755-2721/2026.38358

Table 1. Embodied-carbon performance by public-building type

Building type	Adaptive reuse (kg CO_2e/m^2)	New construction (kg CO_2e/m^2)	Avoided carbon (kg CO_2e/m^2)	ECSR	t
Educational (n = 5)	455.1 ± 50.3	856.4 ± 74.8	401.3 ± 47.2	46.8 ± 4.9%	19.01***
Administrative (n = 5)	486.9 ± 56.8	828.1 ± 63.4	341.2 ± 42.6	41.2 ± 5.4%	17.91***
Cultural (n = 5)	460.8 ± 69.7	878.6 ± 95.5	417.8 ± 61.3	47.6 ± 6.3%	15.24***
Community-service (n = 5)	477.0 ± 58.9	806.0 ± 70.6	329.0 ± 45.8	40.8 ± 4.7%	16.06***
Overall (n = 20)	470.0 ± 61.4	842.3 ± 78.6	372.3 ± 54.7	44.1 ± 5.8%	30.44*

**Note: Values are mean ± SD. **p < 0.001.*

4.2. Component-level contributions to embodied carbon reduction

Structural elements contribute 222.6 ± 38.4 kg CO_2e/m^2 of avoided emissions, equal to 59.8 ± 7.1% of the total. Envelope retention contributes 75.9 ± 19.6 kg CO_2e/m^2, interiors 42.1 ± 14.3 kg CO_2e/m^2, and services 31.7 ± 11.8 kg CO_2e/m^2.

4.3. Relationship between structural retention and carbon saving performance

Mean structural retention is 78.6 ± 8.9%. ECSR correlates strongly with retention rate ($r = 0.81$, 95% CI [0.58, 0.92], $p < 0.001$). After adjustment, retention remains the strongest predictor ($\beta = 0.671 \pm 0.112$, $p < 0.001$), while façade replacement and retrofit intensity are negative.

4.4. Carbon reduction differences across public building types

Cultural buildings record the highest ECSR at 47.6 ± 6.3%, followed by educational buildings at 46.8 ± 4.9%. Administrative and community-service buildings achieve 41.2 ± 5.4% and 40.8 ± 4.7%, respectively.

4.5. Sensitivity of carbon performance to service life and replacement assumptions

Across 10,000 Monte Carlo runs, median ECSR is 42.8%, with a 95% uncertainty interval of 31.6–53.7%. Retention near 60% reduces savings to 29.7 ± 4.6%, whereas retention near 95% raises them to 54.2 ± 5.1%. A 30-year period produces 39.4 ± 5.2%, and a 70-year period 45.7 ± 6.1%.

5. Discussion

5.1. Structural retention as the primary carbon preservation mechanism

The structural retention principle underlies the process of retaining embodied carbon in buildings through the adaptive reuse process. The heavy weight of reinforced concrete structure, along with cement and steel, results in considerable emissions during production and construction; thus, the avoidance of reconstruction creates value that cannot be substituted by any other measure. The above processes confirm the above trend.

DOI: 10.54254/2755-2721/2026.38358

5.2. Trade-off between retrofit intensity and carbon reduction

As intervention intensity increases, the gains from reuse diminish. Replacing facades, rearranging spaces, and doing major renovations involves bringing in new materials such as glass, aluminum, insulation, partitions, and finishings, which means that some of the structural gains are lost. The same percentage of reuse may result in different ECSR figures.

5.3. Implications for public building renewal decisions

The framework allows carbon impacts to be assessed before demolition becomes inevitable. The use of BIM-based status coding shows the impact of keeping or demolishing the different groups of components, while the normalized LCA metrics allow for comparing the impacts across buildings of various sizes. Building structure preservation can be considered as one of the screening variables, with the rest being facade renovation and intensity of retrofits.

6. Conclusion

The BIM-based LCA framework evaluates adaptive reuse through material retention, life-cycle replacement, and uncertainty accounting. In the illustrative dataset, adaptive reuse reduces embodied carbon from 842.3 ± 78.6 to 470.0 ± 61.4 kg CO_2e/m^2, with structural retention providing the largest share of avoided emissions. Façade replacement and retrofit intensity reduce this advantage. Integrating Revit, Dynamo, openLCA, regression, and Monte Carlo simulation provides a reproducible basis for carbon-informed renewal of existing public buildings.

References

[1] Aigwi, I. E., Duberia, A., & Nwadike, A. N. (2023). Adaptive reuse of existing buildings as a sustainable tool for climate change mitigation within the built environment. *Sustainable Energy Technologies and Assessments, 56*, 102945.

[2] Guidetti, E., & Ferrara, M. (2023). Embodied energy in existing buildings as a tool for sustainable intervention on urban heritage. *Sustainable Cities and Society, 88*, 104284.

[3] Gursel, A. P., Shehabi, A., & Horvath, A. (2023). What are the energy and greenhouse gas benefits of repurposing non-residential buildings into apartments? *Resources, Conservation and Recycling, 198*, 107143.

[4] Hu, M., & Świerzawski, J. (2024). Assessing the environmental benefits of adaptive reuse in historical buildings: A case study of a life cycle assessment approach. *Sustainable Environment, 10*(1), 2375439.

[5] Fahlstedt, O., Rasmussen, F. N., Temeljotov-Salaj, A., Huang, L., & Bohne, R. A. (2024). Building renovations and life cycle assessment: A scoping literature review. *Renewable and Sustainable Energy Reviews, 203*, 114774.

[6] Teicher, H. M. (2023). Making embodied carbon mainstream: A framework for cities to leverage waste, equity, and preservation policy to reduce embodied emissions in buildings. *Journal of Environmental Studies and Sciences, 13*, 404–418.

[7] Guignone, G., Calmon, J. L., Vieira, D., & Bravo, A. (2023). BIM and LCA integration methodologies: A critical analysis and proposed guidelines. *Journal of Building Engineering, 73*, 106780.

[8] Teng, Y., Xu, J., Pan, W., & Zhang, Y. (2022). A systematic review of the integration of building information modeling into life cycle assessment. *Building and Environment, 221*, 109260.

[9] Tam, V. W. Y., Zhou, Y., Shen, L., & Le, K. N. (2023). Optimal BIM and LCA integration approach for embodied environmental impact assessment. *Journal of Cleaner Production, 385*, 135605.

[10] Kouka, D., Cardinali, G. D., Messina, G., & Barreca, F. (2025). BIM-based post-occupancy analysis of energy use and carbon impact in adaptive reused buildings: A case study of an olive mill in Southern Italy. *Results in Engineering, 26*, 105150.