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Research Article

Assessing Renovation-Avoided Carbon Emissions: A Comparative Life Cycle Assessment and the Influence of LOD on a Building Use Conversion Project

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Abstract

Renovating existing buildings has emerged as a decisive means of mitigating environmental impacts from buildings. However, estimating life-cycle environmental impacts remained challenging, as rapid early-stage assessments often differed substantially from results from detailed models. This study conducted a comparative Life Cycle Assessment (LCA) of an existing building that underwent adaptive reuse, comparing embodied carbon savings against a demolition and new-build scenario. It isolated the intrinsic material burdens and end-of-life processes of different design scenarios, offering insights into the environmental implications of choosing renovation and adaptive reuse versus demolition and rebuilding. The results demonstrated a 68% reduction in emissions when renovation was chosen and highlighted the relative contributions of different building stages and materials. Significant carbon savings of more than 2,500 metric tons CO_2e were measured, stemming mainly from the retention and reuse of high-impact structural materials such as concrete and steel, which together accounted for more than 93% of the total savings. This study also assessed the impact of Level of Development (LOD) on LCA results, demonstrating that a highly detailed building model at LOD 350, compared with LOD 200, produced a 45.8% variation in results. This contribution highlighted the importance of clearly defining LOD levels when using LCA results to support carbon-reduction decisions. Ultimately, this study provided an empirical case-study benchmark for future LCA studies on adaptive reuse projects, and offered actionable insights for architects, engineers, and policymakers seeking to prioritise adaptive-reuse strategies and appropriate LOD definitions as pathways to accurately meet carbon-reduction targets and support a net-zero future.

Keywords: Adaptive reuse; Building Information Modelling; Embodied carbon; Level of development; Life Cycle Assessment.

Highlights

- Comparative BIM-based LCA of existing building evaluates adaptive reuse versus demolition and reconstruction.
- Adaptive reuse is assessed to result in 70% lower overall emissions.
- Retaining core structural materials like concrete and steel delivers the largest carbon savings.
- LCA accuracy is shown to depends strongly on BIM level of development (+/- 45.8% delta in total EC).

1 Introduction

The building and construction sector is responsible for approximately 40% of global carbon dioxide emissions, with 11% attributed specifically to embodied carbon from building materials (Mlote, Budig, & Cheah, 2024; Global Alliance for Buildings and Construction, 2020). As operational energy efficiency improves due to building codes and renewable technologies, the relative importance of embodied emissions continues to rise (Pomponi & Moncaster, 2016, 2017).

There is an increasing pressure to decarbonise the built environment, especially in rapidly growing urban cities, to control material consumption and prevent resource depletion. In this context, the practice of demolishing ageing structures to make way for new developments presents a significant environmental burden. Adaptive reuse, such as renovating and repurposing existing structures, offers a sustainable alternative that reduces material consumption and minimises waste, moving from a linear to a circular economy approach to maximise resource efficiency throughout buildings' entire life cycle (Mlote et al., 2024; Mlote, Cheah, & Ortner, 2025; Wilkinson, James, & Reed, 2009; Askar, Bragança, & Gervásio, 2021; Schmidt, Eguchi, Austin, & Gibb, 2010).

This study investigated the environmental benefits of renovation through a comparative Life Cycle Assessment (LCA) of an existing building in Singapore that underwent adaptive reuse, comparing the embodied carbon savings against a demolition and new-build scenario.

The study quantified the avoided embodied carbon resulting from the retention and reuse of existing structural and envelope systems. By isolating the product stage (A1–A3) and end-of-life stages (C–D) of the life cycle, the study provided focused insights into the intrinsic material burdens and end-of-life impacts of both pre- and post-renovation scenarios and clarified the carbon savings achievable through material retention.

In an urban context like Singapore, where land scarcity and sustainability goals intersect, adaptive reuse offers a more sustainable alternative to new construction. This research provided a case-study benchmark for future LCA studies and offered decision-support insights for architects, engineers, and policymakers aiming to meet carbon-reduction targets through circular design principles.

2 Methodology

2.1 Case Study

The subject of this analysis was a mid-rise office building of 5839.47 m^2 gross floor area, constructed in 1978 in Singapore using a conventional reinforced concrete frame system (Figure 1). The structure underwent a comprehensive renovation into a co-living residential facility while maintaining much of its original frame and vertical elements. This case exemplified a real-life scenario where renovation aimed to serve both functional and environmental objectives.

The study evaluated three main scenarios (Figure 2):

- **Scenario 1: (baseline)** – the pre-renovation as-is condition of the original office building,
- **Scenario 2:** full demolition of the original building and a total reconstruction of a new co-living residential facility,
- **Scenario 3:** partial demolition and adaptive reuse of the original building as a co-living residential facility.

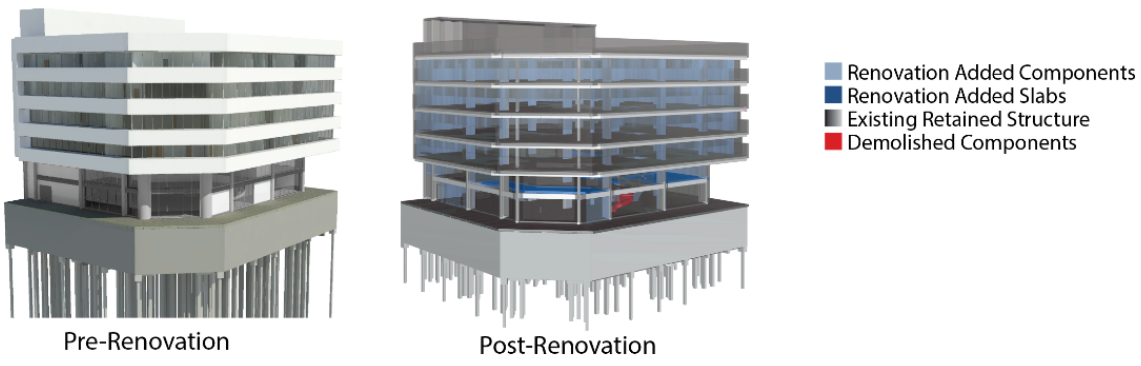

Figure 1. The case study building (Source: authors).

2.2 Scope: Life Cycle Assessment

To isolate the direct material-related impacts, the scope of the Life Cycle Assessment (LCA) was limited to the product stage, specifically modules A1–A3 and end-of-life (C–D), in accordance with the EN 15978 standard. The end-of-life scenarios are defined to reflect the Singapore Waste Statistics (National Environment Agency, 2023; CEN, 2011). These stages encompass the extraction and processing of raw materials, manufacturing, transportation to the construction site and end-of-life processing. Excluded from this analysis were the construction (A4–A5) and use (B) phases, thereby ensuring a focused Product and End of Life Stages comparison of embodied carbon profiles for both pre- and post-renovation scenarios (Figure 2).

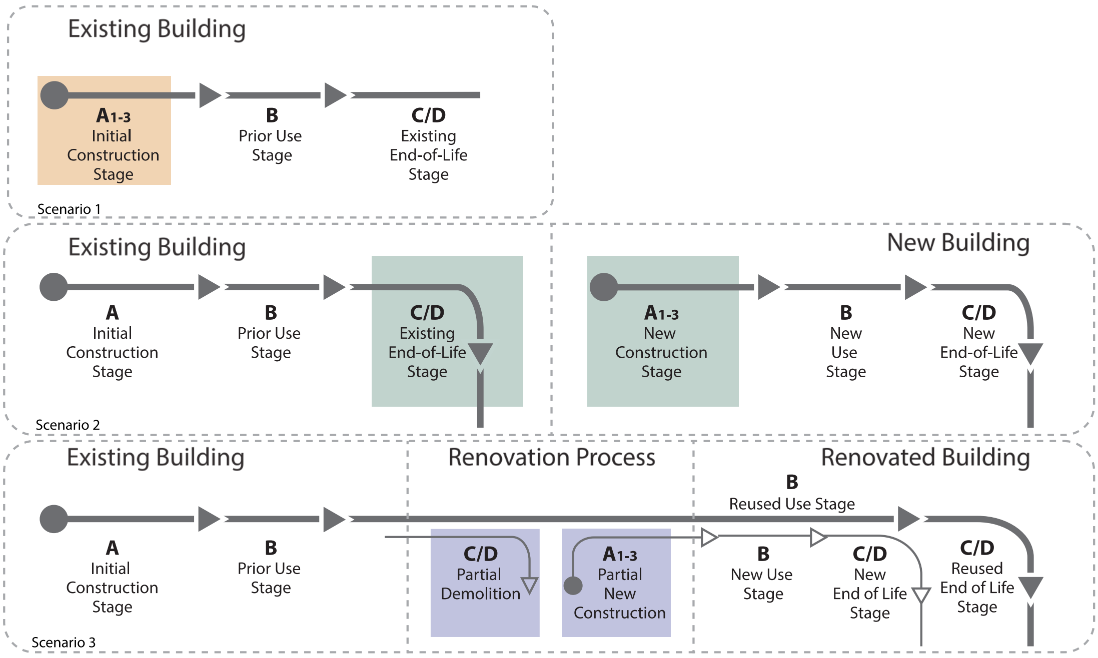

Figure 2. Comparison Scope (Source: authors).

This boundary selection enabled a clear evaluation of embodied carbon (EC) savings linked to material retention, without interference from variability in operational energy use, maintenance practices, or demolition techniques. The methodology reflected the embodied burdens directly attributable to design and construction choices, and end of life decisions. The comparative approach enabled attribution of avoided emissions to specific material systems retained in the renovation, aligning with recent best practices in building circularity assessment. The choice of scope allowed for a consistent baseline to evaluate the embodied carbon increments or savings from demolition versus adaptive reuse.

2.3 Data Sources and Modelling Tools

Detailed material take-offs were derived from the Building Information Modelling (BIM) models constructed in Autodesk Revit. These models were precisely designed to reflect the as-built conditions of the existing structure and the proposed renovation designs, making use of the documentation provided by the building owner.

Each material layer and component within the BIM environment was manually mapped to corresponding material categories and datasets within the One Click LCA software, which offers access to an extensive library of Environmental Product Declarations (EPDs) and background databases, such as CML and ecoinvent (CML-Department of Industrial Ecology, 2016; Wernet et al., 2016). Special care, by the research team, was taken to match each Revit-defined material with the most regionally and technologically appropriate LCA dataset, ensuring representativeness of carbon factors. A detailed mapping process was necessary to ensure accuracy in the final LCA results and the ultimate comparison analysis.

Once modelled and mapped, the resulting embodied carbon values for each material and system, in each scenario, were exported from One Click LCA. This allowed for customised post-processing, where results were organised into Construction Specifications Institute (CSI) MasterFormat divisions, which include Concrete, Masonry and Metals, among others (Carroll-Coelho & Riso, 2024). Manual analysis and graphing were performed to visualise comparative impacts, enabling cross-sectional insights across the CSI divisions.

2.4 Carbon Savings Assessment

The evaluation of avoided carbon emissions was conducted through a comparison of total Global Warming Potential (GWP) between the pre-renovation (baseline) and post-renovation (adaptive reuse) design states. Material-level GWP values were aggregated for both cases based on the A1–A3 and C-D results exported from One Click LCA. This allowed for side-by-side quantification of carbon intensities and total GWP associated with each scenario.

The retained elements, primarily structural components such as columns, beams, load-bearing walls and foundation, were treated as carbon savings in the renovated scenarios, under the assumption that their reuse avoided the production and transport of equivalent new materials. The analysis emphasised high-impact materials such as reinforced concrete and structural steel, which have historically accounted for the majority of embodied carbon in mid- to high-rise buildings.

The avoided-impact methodology was consistent with the system boundary logic proposed by Hasik et al. (2019), which distinguishes between preserved and newly introduced material systems. By isolating the product stage, the study sought to measure the embodied carbon cost of demolition-and-rebuild approaches and highlight the benefits of adaptive reuse strategies. Operational stage emissions were not addressed in any of the scenarios presented in this study. Emissions from mechanical, electrical and plumbing systems were not included in this assessment (Figure 3).

BUILDING SYSTEMS							
STRUCTURE		EXTERIOR		INTERIOR		SYSTEMS	
Foundation	✓	Walls	✓	Walls	✓	Mechanical	☒
Substructure	✓	Roofs	✓	Ceilings	✓	Electrical	☒
Superstructure	✓	Windows & Glazing	✓	Floors	✓	Plumbing	☒
		Doors	✓	Doors	✓	Conveyance	☒
				Finishes	✓	Specialty	☒
				Furniture	☒		

Figure 3. Building systems included and excluded from the study (Source: authors' work inspired by Hasik et al., 2019).

2.5 Impact of Detailed Modelling and Carbon Factor Mapping Accuracy

A supplementary investigation was conducted to understand how modelling granularity and material-carbon factor alignment affect the reliability of LCA outcomes. This analysis was significant, as corroborated by previous studies (Pomponi & Moncaster, 2018), who emphasised that modelling choices can lead to two-fold differences in carbon estimates. The mapping of embodied carbon factors and the accuracy of geometry and quantities both play critical roles in determining the credibility of LCA results.

Here, model detail levels were grouped into three categories to approximately align with BIM Level of Development (LOD): low detail (~LOD 100–200) where elements are generic or schematic with approximate geometry and quantities; moderate detail (~LOD 200–300/350) where elements are modelled as specific systems with geometry accurate in quantity, size, shape, location, and orientation; and high detail (~LOD 350-500) where elements include detailing/fabrication/assembly information and, when field-verified, as-built accuracy, supporting reliable quantity take-off and material and EPD mapping (Abualdenien & Borrmann, 2022). It should be noted that Level of Development (LOD) and Level of Detail (LoD) are different concepts: LoD describes the graphical/geometric richness of a model element, whereas LOD denotes the maturity and reliability of its information for downstream use (such as quantity take-off and LCA); thus, an element may be highly detailed (high LoD) yet still low in development (low LOD) if its information remains provisional (Abualdenien & Borrmann, 2022). Importantly, LOD, which represents the reliability and not just visual detail, may differ from international specifications, potentially leading to inconsistent interpretations if not explicitly stated in case studies.

Clearly defining the LOD of a model is crucial in embodied carbon assessments because it directly influences the accuracy of material quantification and the selection of carbon factors. A lower LOD model may require reliance on generic assumptions or average datasets, introducing greater uncertainty and unreliability into the results. Conversely, a higher LOD with well-mapped materials allows for more precise and reliable calculations. This variation means that embodied carbon results across studies may not always be directly comparable without considering the underlying LOD and modelling assumptions of the case studies used.

Table 1 below summarises sample buildings from peer-reviewed studies, categorised by building type, gross floor area (GFA), estimated GWP from material contributions, and the estimated BIM model detail level.

Table 1. GWP variances and relevance to model details (Source: authors).

Reference	Building Type	Typology	GFA (m^2)	Carbon Intensity ($kgCO_2e/m^2$)	Estimated Total GWP (tCO_2e)	Estimated Model Detail level
Scheuer et al., 2003 [18]	Institutional	University	7300	647	4,725	High detail
Hasik et al., 2019 [15]	Plant, repurposed to office	2-Storey stand-alone building	5,500	470	2,930	Moderate detail
Asif et al., 2007 [19]	Residential	Single dwelling	120	236	28	Low detail

These cases and prior research done by Pomponi and Moncaster (2018), demonstrate that GWP estimates may vary according to model fidelity. Key contributors to potential discrepancies in LCA results could include:

- Less detailed modelling or grouping of distinct material layers into aggregated assemblies,
- Incomplete representation and accounting of structural components (such as the exact amount of rebar reinforcements used),
- Use of default or average EPDs rather than location-, material- and process-specific datasets.

To assess this with relevance to the case study used in this research, a secondary building model was developed in Revit, representing a generic (lesser-detailed LOD 200) structure of the same building, which was analysed using simplified material assignments and default component libraries. Specifically, in this LOD 200 model, the rebar reinforcements were not modelled in detail, and instead all elements which needed reinforcements were mapped in One Click LCA as a combined carbon factor for reinforced concrete elements; for example, "*concrete slab including reinforcements*".

3 Results

3.1 Total Global Warming Potential (GWP)

Scenario 3, which considered renovation with partial material reuse, resulted in a 70% reduction in embodied carbon compared to Scenario 1 (the pre-renovation baseline), and a 68% reduction compared to Scenario 2 (full demolition and new construction) (Table 2). This was equivalent to total savings of 2,552 tCO_2e (2.552 Million $KgCO_2e$) by choosing to renovate and reuse over demolition and rebuilding. These savings were primarily attributed to the retention of structural materials such as concrete and metals, which were the major contributors to embodied carbon in conventional new-build scenarios.

Table 2. Embodied Carbon Comparison by Scenario (Source: authors).

Scenario	GFA (m^2)	Carbon Intensity ($kgCO_2e/m^2$)	Total GWP (tCO_2e)
Scenario 1	5,839	698	4,075
Scenario 2	4,888	771	3,766
Scenario 3	4,888	249	1,215

3.2 Material-Level Analysis

At the material level, the most substantial reductions in embodied carbon were observed in concrete and metals (Table 3). In Scenario 3, concrete-related emissions dropped by 91.8% compared to Scenario 1, and by 91.7% compared to Scenario 2. Similarly, metal emissions in Scenario 3 were reduced by 62% relative to Scenario 2, reflecting the reuse of the original structural frame and foundation systems.

The combined avoided emissions from concrete and metals accounted for approximately 93.4% of the total embodied carbon savings between Scenario 2 and Scenario 3, representing 2,382 tCO_2e of the total 2,551 tCO_2e avoided. Concrete alone contributed 50.3% of these savings, while metals contributed a further 43.1%, confirming that the overall reduction was driven primarily by the retention of high-impact structural materials rather than by smaller reductions across secondary material categories.

Table 3. Embodied Carbon Comparison by CSI Divisions in tCO_2e (Source: authors).

Category	Scenario 1	Scenario 2	Scenario 3
Concrete	1,414	1,399	116
Masonry	302	153	150
Metals	1,887	1,779	680

Wood, Plastics and Composites	43	132	129
Thermal and Moisture Protection	4	5	0
Openings	236	139	118
Finishes	189	159	20

Other categories like masonry and openings showed more modest reductions between Scenario 2 and Scenario 3, indicating partial replacement or upgrades. Figure 4 presents a graphical comparative breakdown of GWP contributions by CSI divisions across all three scenarios. The results demonstrated that Scenario 3, which incorporated selective demolition and reuse, achieved significant reductions across all divisions.

Reused structural systems, particularly concrete, contributed only 8% of their original GWP compared to Scenario 1, illustrating the high carbon-saving potential of adaptive reuse strategies.

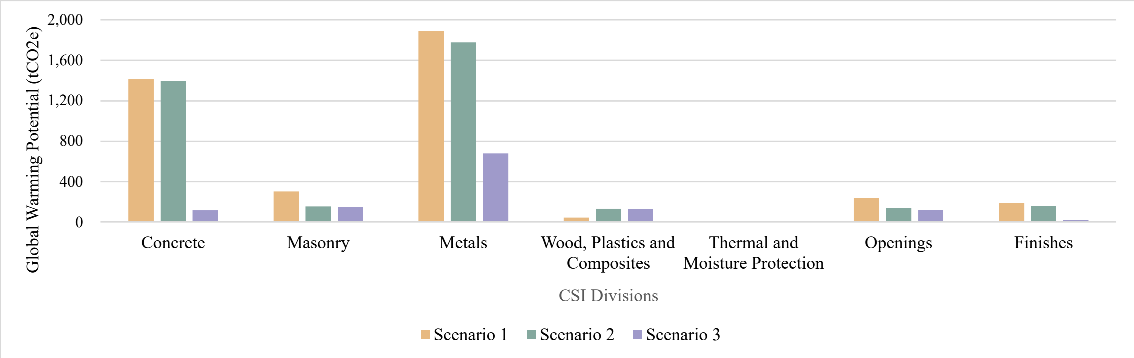

Figure 3. GWP comparison across all material categories (Source: authors).

3.3 Accuracy and Modelling Depth

This study's highly detailed BIM model (LOD 350) and precise material-to-EPD matching facilitated a granular view of embodied carbon contributions by element. Building on the previously shown Table 1, a comparative exercise using a moderately detailed model (LOD 200) of similar building characteristics demonstrated a significant underestimation of embodied emissions, with a 45.8% difference (Table 4). In absolute terms, the LOD 200 model underestimated embodied carbon by 1,867 tCO_2e relative to the LOD 350 model. This nearly 2,000 metric-ton CO_2e discrepancy highlighted how simplifications in geometry, material assignments, and carbon factor selection could significantly skew LCA results.

Table 4. *GWP variances and relevance to model details*

Reference	Model Detail level	Building Type	Typology	GFA (m^2)	Total Embodied Carbon (tCO_2e)
This Study	High detail (LOD 350 excluded MEP)	Office (Pre-Renovation)	Commercial	5,839	4,076
	Moderate detail (LOD 200)	Office (Pre-Renovation)	Commercial	5,839	2,209

These results were consistent with the embodied carbon performance gap highlighted by Pomponi and Moncaster (2018), wherein modelled carbon at the design stage often fails to align with real-world material use and procurement choices.

4 Discussion

4.1 Scenario Comparison

The results of this study highlighted the environmental value of retaining existing structural systems and minimising the need for new material inputs. The significant reduction in embodied carbon, 70.2% compared to the pre-renovation baseline (Scenario 1) and 67.8% compared to full demolition and new construction (Scenario 2), confirmed that adaptive reuse strategies, as modelled in Scenario 3, could serve as a powerful lever in climate mitigation efforts.

Among the materials analysed, concrete and metals emerged as dominant contributors to embodied emissions in both Scenario 1 and Scenario 2, collectively accounting for about 3,200 tCO_2e. In Scenario 2, concrete and metals made up 84.4% of total embodied carbon, but only 65.6% in Scenario 3, highlighting both the savings and the shift in emissions profile after structural reuse. This finding aligned with broader literature identifying these materials as major carbon hotspots due to their energy-intensive manufacturing processes (Hasik et al., 2019). In Scenario 3, retaining the original foundation, beams, columns, steel reinforcements, and most of the concrete slabs led to a 91.8% reduction in concrete emissions and a 63.9% reduction in metal-related emissions compared to Scenario 2, nearly eliminating their associated A1–A3 impacts. This demonstrated the substantial carbon benefit of structural reuse and reinforced the importance of preserving high-impact materials where possible.

Beyond structural components, the comparative data revealed that even non-structural materials such as internal partitions, openings, and finishes contributed meaningfully to overall embodied emissions. In Scenario 3, Finishes saw an 87.3% reduction compared to Scenario 2, and emissions from thermal and moisture protection materials were entirely avoided. This highlighted how thoughtful material retention across both core and peripheral building systems could substantially reduce a project's environmental footprint. These results also reinforced the necessity of considering the full material palette, not just the frame or envelope, when aiming for low-carbon outcomes.

The methodology adopted in this study, combining detailed BIM-derived quantities, CSI MasterFormat mapping, and LCA through One Click LCA, allowed for precise quantification of material-specific impacts. This approach enables a level of resolution that supports informed decision-making for the developers and designers and can be adapted as a replicable framework for future assessments of renovation and reuse potential in the built environment.

From a policy perspective, these findings showed the possibility of tightening embodied-carbon requirements so that codes stipulate progressively lower embodied carbon thresholds, making adaptive reuse increasingly necessary to comply. For example, stricter A1–A3 caps could be set for demolition-and-rebuild projects while providing streamlined compliance pathways or credits for structural retention and material reuse. Financial incentives such as carbon pricing, renovation tax incentives, and performance-based embodied-carbon benchmarks would further shift decisions toward reuse.

Some limitations of this study must be acknowledged. This study excluded emissions from Mechanical, Electrical, and Plumbing (MEP) systems, which could contribute further to embodied impacts. Future studies could build on this work by incorporating MEP data and investigating varying assumptions around partial material upgrades or refurbishment. Furthermore, this study did not address emissions from the operational phase of the building lifecycle.

4.2 Accuracy and Modelling Depth as Determinants of Carbon Quantification

As building policies continue to include carbon thresholds and reporting requirements, consistent modelling standards must be considered to ensure results are both comparable and actionable. As designs progress from concept to detailed stages, greater fidelity in BIM models and the accuracy of carbon factor mapping become imperative for credible carbon reduction planning. Practitioners should recognise that while early-stage LCA using simplified models can provide indicative insights, decision-making on embodied carbon reduction must be informed by more comprehensive modelling. Where feasible, BIM-linked LCAs should involve higher LOD models that include detailed material definitions, volumetric validation, and the use of verified carbon factors matched to each component.

The variation in results across low, moderate, and highly detailed LCA models, such as those shown in Table 1 and Table 4, illustrated the profound influence that modelling accuracy and material mapping had on the calculated embodied carbon of buildings. This inconsistency raised a critical point: current global LCA practices may often underestimate or overestimate embodied carbon values depending on data quality, software assumptions, and modelling fidelity. As evidenced, projects relying on simplified, inventory-based methods reported significantly lower or broader ranges of carbon impacts compared to those based on detailed material take-offs and comprehensive datasets.

The discrepancy in LCA results across LOD levels was not just a methodological issue; it carried real-world implications: if policymakers, designers, or industry stakeholders were planning future carbon targets, regulations, or decarbonization strategies based on imprecise LCA results, they could inadvertently misjudge the actual emissions landscape. Carbon budgets and regulatory limits defined on inaccurate building LCA results could be overly lenient or unreasonably stringent. This finding emphasised the need to further investigate how a model's LoD, LOD, assumptions, and data sources influence LCA outcomes, and more importantly, how these discrepancies can be transparently reported and corrected. Only through such rigor can carbon accounting truly reflect the environmental impact of buildings, and mitigation strategies be effectively aligned with reality.

It is important to acknowledge, however, that in some cases, not all projects may require highly detailed LCA models. For early-stage assessments, preliminary benchmarking, or broad policy scoping, low or moderately detailed models may offer sufficient insights, particularly when rapid comparisons or strategic guidance are the priority. Improvements in the application of machine learning techniques to building LCA estimation may help either to achieve more accurate results, or at a minimum, to have a better understanding of the range of error likely in EC estimation for the early design process (Budig et al., 2021).

The key takeaway from this research is not to mandate a universal LOD, but rather to highlight that modelling accuracy is a significant factor in LCA outcomes. Being transparent about the LOD used allows practitioners and decision-makers to understand the confidence level of their results, and to assess how modelling choices may affect future carbon accounting, certification pathways, or design decisions. Future research should integrate LOD classification into embodied carbon reporting, develop benchmarks that account for modelling resolution, and establish transparent margins of error for each LOD level. This would ensure that when results are used for policymaking, certification, or setting decarbonization targets, stakeholders understand both the confidence level and the limitations inherent to the model's development stage.

5 Conclusions

This study emphasised the significant environmental potential of adaptive reuse as a strategy for reducing embodied carbon in the built environment. By applying a highly detailed Life Cycle Assessment (LCA) to a 1978 reinforced concrete-framed building in Singapore, the analysis demonstrated that renovation (Scenario 3), with strategic material retention, achieved a nearly 70% reduction in embodied carbon relative to a full demolition and reconstruction scenario (Scenario 2). This reduction translated to approximately 2,552 tons of avoided CO_2 emissions, primarily due to the preservation of carbon-intensive elements such as concrete and structural steel.

In parallel, the study investigated how model detail and carbon factor fidelity influence LCA outcomes. A comparison between models of the same building with different LODs revealed a 45.8%

underestimation of embodied carbon when relying on simplified low-detail modelling and default material libraries.

These findings carried important implications for both practice and policy. As governments and industry stakeholders respond to decarbonization imperatives, this study supported the prioritisation of renovation over demolition in regulatory and planning frameworks, the integration of detailed, transparent LCA modelling in carbon assessment protocols, and the development of standards and guidance for LCA accuracy thresholds in early- vs late-stage design phases.

Future research should expand to integrate operational carbon impacts (including A4–A5 and B stages) and evaluate how adaptive reuse strategies perform under dynamic urban constraints, such as circular material flows, density limits, and future retrofit needs. Ultimately, this research affirmed that preserving and upgrading existing structures is not only a sustainable choice but also a scientifically quantifiable, high-impact pathway toward a lower-carbon, more resilient built environment. As cities strive toward net-zero construction, evidence-based reuse strategies like Scenario 3 offer a clear blueprint for balancing development with decarbonisation.

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Ethical Approval Declaration

The study was conducted in accordance with established standards for research integrity and ethics. The authors declare that this research did not involve human participants or animals, and therefore, ethical approval was not required.

Informed Consent Statement

Not Applicable

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Data Availability Statement

The data supporting the findings of this study are available from the author upon reasonable request.

Conflicts of Interest

The authors declare no conflict of interest.

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