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Adaptive Reuse as a Low-Carbon Design Strategy in the Indian Context: An Embodied Carbon Comparison with New Construction

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Abstract

The building and construction sector is one of the largest contributors to global greenhouse gas emissions, accounting for a significant share of both operational and embodied carbon. While regulatory frameworks such as the Energy Conservation Building Code (ECBC 2017) have improved operational energy performance in India, emissions associated with material extraction, manufacturing, transportation, and construction remain largely unregulated. As buildings become more energy-efficient, embodied carbon constitutes an increasing proportion of lifecycle emissions, particularly in reinforced concrete commercial structures.

This study evaluates adaptive reuse as a low-carbon design strategy by comparing the upfront embodied carbon of an adaptive reuse workplace and a newly constructed commercial office building in Bengaluru, India. The analysis focuses on lifecycle stages A1–A5, representing emissions generated prior to building occupancy.

A comparative case study methodology is adopted using secondary data sources, institutional benchmarks, and lifecycle assessment principles. Embodied carbon values are normalized per square meter ($kgCO_2e/m^2$) to ensure comparability. Results indicate that conventional reinforced concrete office buildings typically exhibit embodied carbon intensities between 450–750 $kgCO_2e/m^2$, whereas adaptive reuse projects range between 300–500 $kgCO_2e/m^2$ depending on structural retention levels.

The findings suggest that adaptive reuse can reduce upfront embodied carbon emissions by approximately 30–50%. Structural retention emerges as the primary driver of this reduction. The study highlights the need to integrate embodied carbon assessment into architectural practice and policy frameworks in rapidly urbanising Indian cities.

Key Words: Adaptive reuse, embodied carbon, lifecycle assessment, sustainable architecture, structural retention,
Bengaluru

1.Introduction

The building and construction sector represents one of the most significant contributors to global greenhouse gas (GHG) emissions and energy consumption. According to the United Nations Environment Programme Global Status Report for Buildings and Construction (UNEP, 2023), the sector accounts for approximately 37% of global energy- and process-related carbon dioxide (CO_2) emissions. These emissions arise from two primary sources: operational carbon and embodied carbon. Operational emissions originate from the energy consumed during a building's use phase, including heating, cooling, lighting, and equipment. Globally, operational energy accounts for roughly 27% of total energy-related emissions, while emissions associated with building materials and construction processes contribute an additional 10–15%, depending on the lifecycle boundary considered (UNEP, 2023; IPCC, 2022).

Within rapidly urbanizing economies such as India, the building sector is expected to experience substantial growth over the coming decades. The International Energy Agency (IEA, 2022) estimates that India's building floor area may nearly double by 2040, driven by population growth, urban migration, and economic expansion. This expansion significantly increases both operational energy demand and material consumption, particularly for energy-intensive construction materials such as cement and steel.

Historically, decarbonization strategies within the built environment have focused predominantly on reducing operational energy consumption. Policies, technological improvements, and energy-efficiency standards have played a major role in improving building performance.

In India, the Energy Conservation Building Code (ECBC 2017) developed by the Bureau of Energy Efficiency (BEE) provides mandatory performance standards for commercial buildings with a connected load greater than 100 kW or contract demand exceeding 120 kVA. ECBC prescribes minimum performance requirements for building envelopes, lighting systems, HVAC systems, and electrical equipment.

The implementation of ECBC has significantly improved operational efficiency in commercial buildings. Studies conducted by the Bureau of Energy Efficiency (BEE, 2017) indicate that ECBC-compliant buildings can achieve energy savings of approximately 25–50% compared to conventional baseline buildings. One commonly used metric for evaluating operational performance is the Energy Performance Index (EPI), measured in kWh/m²/year, which represents the annual energy consumption per unit floor area. High-performance commercial office buildings in India typically achieve EPI values between 70–90 kWh/m²/year, compared to conventional buildings that often exceed 140–180 kWh/m²/year (BEE, 2017; TERI, 2021).

Building envelope design also plays a crucial role in reducing operational energy demand. ECBC guidelines specify performance thresholds for envelope components such as walls, roofs, and glazing systems. For example, the ECBC recommends U-values of approximately 0.409 W/m²K for roofs and 0.44–0.6 W/m²K for walls, depending on climatic zone. Additionally, solar heat gain coefficients (SHGC) for glazing are limited to improve thermal performance and reduce cooling loads (BEE, 2017).

Despite these advancements in operational efficiency, growing attention is now being directed toward embodied carbon, which refers to the greenhouse gas emissions associated with the extraction, manufacturing, transportation, installation, maintenance, and end-of-life disposal of building materials. Unlike operational emissions, embodied carbon is largely “locked in” at the time of construction, meaning that it cannot be easily reduced once materials have been produced and incorporated into a building (Pomponi & Moncaster, 2017).

Embodied carbon is particularly significant in countries where reinforced concrete remains the dominant structural system. In India, reinforced cement concrete (RCC) structures are widely used in commercial office buildings due to their structural robustness, cost efficiency, and construction familiarity. However, the production of cement — a key ingredient in concrete — is extremely carbon-intensive. According to the Confederation of Indian Industry (CII, 2022), the cement sector contributes approximately 7–8% of India’s total CO_2 emissions, while globally it accounts for nearly 8% of anthropogenic CO_2 emissions (IPCC, 2022). Similarly, steel production contributes significantly to industrial emissions due to its high energy requirements and reliance on fossil fuels.

As operational energy efficiency improves through stricter building codes and technological advancements, the relative proportion of embodied carbon in building lifecycle emissions is increasing. Recent lifecycle assessments suggest that embodied carbon may account for 40–60% of total lifecycle emissions in highly energy-efficient buildings, particularly when operational energy demand is minimized (Pomponi & Moncaster, 2017).

In response to these challenges, adaptive reuse has emerged as a promising low-carbon design strategy within sustainable architecture. Adaptive reuse refers to the process of repurposing existing buildings for new functions while retaining substantial portions of their structural and material fabric. Rather than demolishing existing buildings and constructing new ones, adaptive reuse leverages the embodied energy already invested in existing structures, thereby avoiding the emissions associated with new material production and construction activities (Bullen & Love, 2011).

Several international studies have demonstrated the carbon-reduction potential of adaptive reuse strategies. Research conducted by the Preservation Green Lab (2011) found that building reuse can reduce embodied carbon impacts by between 50% and 75% compared to equivalent new construction, depending on the extent of structural retention. Similarly, Cabeza et al. (2014) highlight that extending the lifespan of existing buildings through reuse significantly improves lifecycle environmental performance by distributing embodied emissions over a longer service life.

Within the Indian context, however, empirical studies comparing adaptive reuse and new construction remain limited. Most sustainability initiatives have historically focused on greenfield development and certification frameworks such as IGBC (Indian Green Building Council) and GRIHA (Green Rating for Integrated Habitat Assessment). While these frameworks emphasize energy efficiency, water management, and indoor environmental quality, embodied carbon assessment has only recently begun receiving systematic attention.

Bengaluru provides an ideal context for examining these dynamics due to its rapid urban growth and concentration of commercial office development. The city hosts a significant number of both newly constructed high-performance office buildings and adaptive reuse projects, making it suitable for comparative lifecycle analysis. For instance, buildings such as the CII Sohrabji Godrej Green Business Centre in Hyderabad, although not located in Bengaluru, demonstrate the potential of high-performance green buildings in India, achieving EPI values as low as 55 kWh/m²/year and generating renewable energy through integrated photovoltaic systems (TERI, 2019). However, even such highly efficient buildings retain substantial embodied carbon due to material-intensive construction.

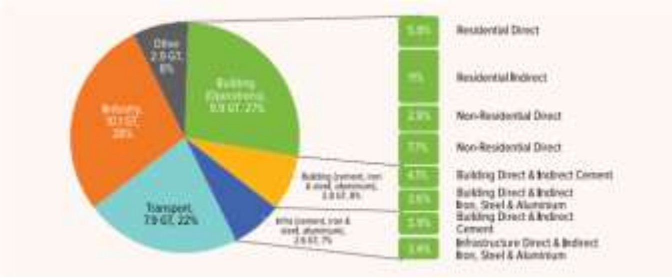
Therefore, strategies that reduce demand for new construction materials, such as adaptive reuse, require systematic evaluation within the Indian building sector. By comparing the embodied carbon implications of adaptive reuse projects with equivalent new construction, researchers and policymakers can better understand the role of reuse in achieving India's climate targets and supporting sustainable urban development.
This study therefore investigates the extent to which adaptive reuse can reduce embodied carbon compared to new construction within Bengaluru's commercial office sector. Using a secondary-data-based lifecycle assessment framework, the research evaluates material composition, embodied carbon factors, and lifecycle impacts associated with representative case studies. Through this comparative analysis, the study aims to contribute to the growing body of knowledge on low-carbon architectural strategies in the Indian context, informing both policy development and design practice.

Sector	CO_2 Contribution
Building Operations	27%
Building Materials	15%
Transport	22%
Industry	28%
Others	8%

1.1 Background of the Study

The building and construction sector represents one of the largest contributors to global greenhouse gas (GHG) emissions. When both operational and material-related emissions are considered, the sector accounts for approximately 37% of global energy- and process-related CO_2 emissions (UNEP, 2023; IPCC, 2022). Traditionally, attention has focused on reducing operational emissions through improvements in building envelope design, HVAC efficiency, and regulatory mechanisms. However, increasing evidence indicates that emissions associated with building materials — commonly referred to as embodied carbon — constitute a significant and growing share of total lifecycle emissions.

Figure 1: illustrates the global distribution of CO_2 emissions by sector, highlighting the contribution of building operations as well as material production associated with the built environment.



(Source https://aeee.in/wp-content/uploads/2024/08/life-cycle-assessment-of-carbon-emissions.pdf?utm_source=chatgpt.com)

As shown in Figure 1, building operations account for approximately 27% of global CO_2 emissions, while emissions from building materials such as cement, iron, steel, and aluminium contribute an additional 15% when direct and indirect impacts are combined (AEEE, 2024). This indicates that the built environment, when viewed holistically, is responsible for over 40% of global energy-related emissions. The figure underscores a critical shift in carbon discourse: while operational performance improvements remain important, embodied carbon embedded within materials is increasingly recognized as a major contributor to lifecycle emissions.

In the Indian context, the building sector accounts for approximately 30–35% of total electricity consumption (Bureau of Energy Efficiency [BEE], 2021). The implementation of the Energy Conservation Building Code (ECBC 2017) has resulted in measurable reductions in operational energy intensity, with ECBC-compliant commercial buildings demonstrating 25–50% energy savings compared to conventional baselines (BEE, 2017). As operational energy demand decreases, embodied carbon assumes a proportionally larger share of total lifecycle emissions, particularly in material-intensive reinforced concrete (RCC) commercial buildings.

Embodied carbon is typically expressed as $kgCO_2e/m^2$ of built area. International benchmarks indicate that reinforced concrete commercial buildings exhibit upfront embodied carbon values between 500–900 $kgCO_2e/m^2$ (RICS, 2017). Indian LCA studies report ranges of approximately 450–750 $kgCO_2e/m^2$ for conventional RCC commercial buildings in metropolitan contexts (TERI, 2021).

These values highlight the need to examine strategies that reduce material demand rather than solely improving operational efficiency.

2. Literature Review

Embodied carbon refers to greenhouse gas emissions associated with the production and construction of building materials. These emissions arise from processes such as raw material extraction, manufacturing, transportation, and on-site construction activities. Materials commonly used in modern construction, including cement, steel, aluminium, and glass, require high energy inputs and contribute significantly to emissions.

Studies report that as buildings become more operationally efficient, the proportion of embodied carbon within total lifecycle emissions increases. In highly efficient buildings, embodied carbon may account for up to 50–60% of total lifecycle emissions. This shift has led to greater attention on material efficiency and construction practices.

Lifecycle Assessment (LCA) is widely used to evaluate the environmental impact of buildings. LCA divides the building lifecycle into stages, including product stage (A1–A3), transport (A4), construction (A5), use (B stages), and end-of-life (C stages). Embodied carbon studies often focus on stages A1–A5, which represent upfront emissions associated with construction.

Adaptive reuse has been identified as a strategy to reduce embodied carbon by retaining existing structural systems. Studies report that preserving structural components can reduce embodied carbon emissions by approximately 30–60%, depending on the level of intervention. This reduction occurs primarily due to decreased demand for new materials and reduced demolition waste.

However, most existing research is based on European and North American contexts. Differences in construction practices, material supply chains, and regulatory frameworks limit direct application to the Indian context. Therefore, there is a need for localized studies that evaluate embodied carbon in Indian cities.

The contribution of different materials to embodied carbon varies significantly depending on structural systems and construction practices. Cement production is one of the largest contributors due to the energy-intensive process of clinker production, which releases carbon dioxide both from fuel combustion and chemical reactions. Steel production also contributes significantly due to high energy requirements during manufacturing.

Other materials such as aluminium and glass have comparatively lower total contributions but still represent substantial embodied emissions due to their processing requirements. In reinforced concrete structures, the combination of cement and steel typically dominates the total embodied carbon footprint. This explains why structural systems account for a large proportion of emissions in commercial buildings.

The embodied carbon associated with construction materials varies significantly depending on their production processes and usage within building systems. Cement and steel are consistently identified as the primary contributors in reinforced concrete structures due to their high energy intensity and widespread application. Cement production involves calcination, a chemical process that releases carbon dioxide independently of energy use, while steel production requires high-temperature processing.

Other materials such as aluminium and glass also contribute to embodied carbon, although their overall share is typically lower compared to structural materials. Aluminium production, for instance, is energy-intensive due to electrolysis processes, while glass manufacturing requires high-temperature furnaces.

Understanding material-specific contributions is essential for identifying opportunities for carbon reduction. Since structural systems dominate embodied carbon profiles, strategies that reduce structural material demand—such as adaptive reuse—offer significant mitigation potential.

2.2 Conceptual Foundations

2.2.1 Carbon Lock-In and Infrastructure Irreversibility

The concept of “carbon lock-in” refers to the irreversible emissions embedded within long-lived infrastructure systems. Once materials such as reinforced concrete and structural steel are produced and incorporated into buildings, their associated emissions are permanently fixed. Unlike operational emissions, which may be reduced over time through technological upgrades or renewable energy substitution, embodied emissions occur prior to occupancy and cannot be retroactively mitigated.

Buildings, due to their long service lives (often exceeding 50 years), represent significant carbon lock-in mechanisms. Decisions taken at the design and construction stage therefore have multi-decade environmental implications.

Building Type	Operational Share	Embodied Share
Conventional	60–70%	30–40%
High-Performance	40–50%	50–60%

2.1 Embodied Carbon in Buildings

Embodied carbon represents the total greenhouse gas emissions associated with the production and construction of building materials. These emissions originate from multiple stages, including raw material extraction, manufacturing processes, transportation to site, and construction activities. In contrast to operational carbon, which is generated during the use phase of a building, embodied carbon is released before the building becomes operational.

In modern construction practices, materials such as cement, steel, aluminium, and glass are widely used due to their structural and functional properties. However, these materials are also associated with high carbon emissions due to energy-intensive production processes. Cement production involves calcination, which releases carbon dioxide as a chemical by-product, while steel

2.2 Transition from Operational to Embodied Carbon

For many years, sustainability approaches in the building sector have concentrated on reducing operational energy consumption, as emissions during the use phase historically formed the largest portion of lifecycle carbon. Operational carbon refers to emissions generated from energy use during building occupancy, including heating, cooling, ventilation, lighting, and equipment. As a result, global building policies, energy codes, and certification systems have traditionally prioritised energy efficiency through improved building envelopes, high-performance mechanical systems, and the incorporation of renewable energy sources.

According to the United Nations Environment Programme (UNEP) Global Status Report for Buildings and Construction (2023), building operations have historically contributed around 27% of global energy-related carbon emissions, while emissions from construction materials and processes account for an additional 10–15%. This distribution has shaped early sustainability strategies, which largely focused on reducing operational energy demand through technological and design improvements.

In the Indian context, similar approaches have been adopted through regulatory frameworks such as the Energy Conservation Building Code (ECBC 2017), developed by the Bureau of Energy Efficiency (BEE). The ECBC sets minimum energy performance standards for commercial buildings with connected loads above 100 kW, addressing aspects such as building envelope efficiency, HVAC systems, lighting power density, and electrical performance. Studies by BEE indicate that buildings designed in compliance with ECBC can achieve energy savings in the range of 25–50% when compared to conventional baseline buildings (BEE, 2017).

Lifecycle carbon assessment typically includes stages:

Lifecycle Stage	Description
A1–A3	Material extraction & manufacturing
A4	Transportation
A5	Construction
B1–B7	Use phase
C1–C4	End of life
D	Reuse / recycling

2.4 Adaptive Reuse as a Carbon Reduction Strategy

Adaptive reuse involves repurposing existing buildings for new functions while retaining significant portions of their structural systems. By preserving structural elements, adaptive reuse reduces the need for new material production, thereby lowering embodied carbon emissions.

The effectiveness of adaptive reuse depends on the extent of structural retention. Partial retention may result in moderate carbon reductions, while extensive retention can significantly reduce embodied carbon. However, adaptive reuse may still require additional materials for retrofitting, including façade upgrades, structural reinforcement, and mechanical systems integration.

Despite these additional requirements, studies consistently indicate that adaptive reuse results in lower embodied carbon compared to new construction.

2.5 Indian Context and Research Gaps

In India, embodied carbon research is still developing. While regulatory frameworks such as ECBC address operational energy performance, they do not account for embodied carbon. This creates a gap in sustainability assessment, particularly in the context of rapidly growing urban areas.

Data availability is another challenge. Detailed material quantity data is often not publicly accessible, making it difficult to conduct precise lifecycle assessments. As a result, many studies rely on generalized benchmarks rather than project-specific data.

These limitations highlight the need for localized research that evaluates embodied carbon within Indian urban contexts using transparent and adaptable methodologies.

2. Methodology

This study adopts a comparative case study approach to evaluate the embodied carbon implications of adaptive reuse and new construction in Bengaluru. The research focuses on commercial office buildings, which represent a significant portion of urban construction activity.

Two case studies are selected: an adaptive reuse workplace and a newly constructed commercial office building. Both cases are located within the same city and represent similar functional typologies, ensuring comparability.

The analysis focuses on lifecycle stages A1–A5, which include material extraction, manufacturing, transportation, and construction processes. Embodied carbon values are expressed in $kgCO_2e$ per square meter to enable comparison between buildings of different sizes.

The methodology involves establishing baseline embodied carbon values for new construction and applying reduction factors based on structural retention in adaptive reuse. Results are presented as ranges to account for variability in data.

This approach ensures consistency while addressing limitations associated with secondary data and lack of detailed material quantities.

3.2 Research Philosophy and Approach

3.2.1 Research philosophy

This research adopts a **post-positivist research philosophy**, which assumes that while environmental phenomena such as carbon emissions can be **measured using scientific methods**, complete objectivity is difficult due to limitations in data availability, methodological boundaries, and uncertainties in lifecycle inventories. Post-positivism is widely used in environmental and built-environment research because it allows researchers to apply **quantitative analytical frameworks while acknowledging uncertainties in empirical data** (Creswell & Creswell, 2018). In the context of building lifecycle assessment, uncertainties frequently arise due to incomplete material inventories, variations in emission factors, and limited access to detailed bills of quantities (BoQs), especially when studies rely on **secondary datasets rather than direct site measurements**.

Within the building sector, **embodied carbon is typically quantified through lifecycle assessment (LCA) frameworks**, which estimate emissions associated with material extraction, manufacturing, transportation, construction, maintenance, and end-of-life processes. International environmental assessment standards such as **ISO 14040/14044 and EN 15978** recommend structured carbon accounting across lifecycle stages (A1–A3 material production, A4–A5 construction, B1–B7 operational stage, and C1–C4 end-of-life processes) (IPCC, 2022; UNEP, 2023). These frameworks form the methodological basis for most contemporary building carbon assessments.

However, in the Indian context, **comprehensive embodied carbon databases and publicly available construction inventories remain limited**, particularly for commercial office buildings. Although initiatives such as the **India Life Cycle Inventory Database (ILCID) supported by the Ministry of Environment and Forests and TERI** have begun addressing this gap, material carbon factors are still frequently derived from international datasets and industry benchmarks (TERI, 2021). Consequently, post-positivist research recognizes that carbon estimates should be interpreted as **probabilistic ranges rather than exact values**.

3.2.2 Research approach

The study adopts a comparative case study approach, integrating quantitative carbon modeling with qualitative document analysis to evaluate the embodied carbon implications of adaptive reuse versus new construction in commercial office buildings. Comparative case studies are widely used in built-environment research to assess the environmental performance of alternative design strategies under real-world conditions (Yin, 2018).

The quantitative component of the research involves estimating embodied carbon intensity ($kgCO_2e/m^2$) for selected case studies using lifecycle carbon benchmarks and structural material retention assumptions. Studies conducted by the Indian Green Building Council (IGBC) and the Confederation of Indian Industry (CII) suggest that embodied carbon intensity for commercial office buildings in India can range between 500–900 $kgCO_2e/m^2$ depending on structural system, material composition, and building height. Reinforced cement concrete (RCC), the dominant structural system in Indian commercial buildings, contributes significantly to this value due to the carbon-intensive production of cement and steel (CII, 2022).

To contextualize embodied carbon analysis within overall building performance, the study also considers operational performance metrics reported in building documentation and sustainability disclosures. For example, energy-efficient commercial buildings complying with ECBC 2017 standards may achieve energy savings of approximately 25–50% compared to baseline buildings, while high-performance green buildings in India often achieve Energy Performance Index (EPI) values between 60–90 $kWh/m^2/year$, compared to conventional commercial buildings that may exceed 150–200 $kWh/m^2/year$ (BEE, 2017; TERI, 2021).

In addition to quantitative modeling, the research incorporates document analysis to verify the scope and extent of adaptive reuse interventions in selected case studies. Project reports, architectural documentation, sustainability certification disclosures (such as IGBC or LEED project reports), and publicly available technical publications are reviewed to identify evidence of structural retention, façade reuse, and material preservation. These documents help determine the proportion of retained structural elements, which directly influences embodied carbon savings.

For instance, internationally documented reuse projects demonstrate that retaining structural frames and foundations can reduce embodied carbon by approximately 50–70% compared to full demolition and reconstruction, depending on the level of material retention (Preservation Green Lab, 2011). Applying similar retention-based modeling in the Indian context enables comparative analysis between adaptive reuse and equivalent new construction scenarios.

3.3 Research Design and Strategy

The present study adopts a **comparative two-case study research design** to evaluate the extent to which adaptive reuse reduces upfront embodied carbon (A1–A5 stages) compared to equivalent new construction within a controlled urban and climatic context. The comparative case study method is widely recognized in built environment research for examining complex, context-dependent phenomena where experimental manipulation is not feasible (Yin, 2018). Given that embodied carbon outcomes are influenced by structural systems, material sourcing, climatic response, regulatory standards, and urban development pressures, a contextualized case comparison offers methodological robustness.

The research is situated within **Bengaluru, Karnataka**, a metropolitan region characterized by rapid commercial real estate expansion, high redevelopment intensity, and significant embodied material demand. According to the Ministry of Housing and Urban Affairs (MoHUA, 2018), India is projected to reach nearly 600 million urban residents by 2030, intensifying construction activity across major metropolitan centers. Bengaluru, as a leading IT and commercial hub, represents a high-growth urban context where demolition-versus-retention decisions are frequent.

The study compares:
Case A: Adaptive Reuse Commercial Workplace
Case B: Newly Constructed Commercial Office Building
Both cases serve workplace functions, thereby controlling for functional typology while isolating structural and material pathway differences.

3.3.1 Rationale for Selecting Bengaluru

Bengaluru falls within the **composite climatic zone** under the Energy Conservation Building Code (ECBC 2017), characterized by moderate seasonal variation, significant cooling demand, and transitional humidity periods (Bureau of Energy Efficiency [BEE], 2017). The composite climate classification ensures that both buildings operate under similar environmental conditions, reducing climatic variability in comparative analysis.

ECBC 2017 prescribes climate-specific performance benchmarks, including:
Maximum wall U-values (approx. 0.440 W/m²K for composite climate)
Roof U-values (approx. 0.261–0.409 W/m²K depending on construction)
Window-to-wall ratio (WWR) cap of 40% (prescriptive compliance)
Solar Heat Gain Coefficient (SHGC) limits varying by orientation
Target Energy Performance Index (EPI) values typically between 90–120 kWh/m²/year for compliant commercial buildings (BEE, 2017)
Because both case studies are located in Bengaluru, they are governed by identical climatic design constraints and regulatory frameworks, strengthening internal validity.

3.3.2 Comparative Design Logic: "Most-Similar Context" Strategy

The study employs a **most-similar systems design**, a comparative logic commonly used in case study research to isolate the influence of one key independent variable while holding contextual variables constant.

In this research:
Geography: Same metropolitan region (Bengaluru)
Climate: Same composite climate classification
Function: Commercial office / workplace typology
Regulatory regime: ECBC 2017 applicability
Urban development pressures: Comparable redevelopment intensity

The primary differentiating variable is:
Construction Pathway (Adaptive Reuse vs New Construction)
This design allows the study to attribute differences in embodied carbon intensity primarily to structural retention versus full material replacement, rather than external environmental factors.

3.3.3 Functional Unit and Normalization Strategy

Embodied carbon comparisons across buildings of varying sizes require normalization. Following international lifecycle assessment conventions (ISO 14040; RICS, 2017), this study adopts:

Functional Unit: kgCO₂e per square meter (kgCO₂e/m²)
This area-based metric enables comparison between:
A reused mid-scale workplace
A newly constructed commercial office tower

Normalization per square meter ensures comparability independent of gross floor area differences.

Parameter	Justification
Unit of analysis	Gross built-up area (m²)
Impact metric	kgCO₂e/m²
Lifecycle boundary	A1–A5 (Upfront embodied carbon)
Comparative control	Same typology and climate

3.3.4 Boundary Definition and Analytical Scope

This study adopts a cradle-to-site boundary (A1–A5 stages):

- A1–A3: Raw material extraction and manufacturing
- A4: Transportation to site
- A5: Construction/installation

Operational energy (B6) and end-of-life (C modules) are excluded to focus specifically on upfront carbon differences attributable to structural retention.

This boundary selection is justified by the IPCC (2022), which emphasizes that upfront emissions represent a critical near-term mitigation opportunity due to immediate atmospheric impact.

3.3.5 Integration of Operational Performance Benchmarks

Although operational carbon is not modeled directly in this study, operational benchmarks provide contextual framing. ECBC-compliant commercial buildings demonstrate:

- 25–50% operational energy savings over baseline buildings (BEE, 2021)
- EPI reductions from 180–250 kWh/m²/year (non-compliant) to 90–120 kWh/m²/year (compliant)
-

In high-performance commercial buildings, embodied carbon can represent a larger proportion of lifecycle emissions as operational energy intensity decreases (UNEP, 2023).

This contextual relationship strengthens the importance of analyzing embodied emissions in redevelopment decisions.

4. Results and Analysis

The comparative analysis reveals a clear and consistent difference in embodied carbon intensity between new construction and adaptive reuse pathways. Conventional reinforced concrete (RCC) commercial office buildings typically exhibit embodied carbon values ranging between 450–750 $kgCO_2e/m^2$. These values are primarily driven by the high material demand associated with structural systems, particularly cement and reinforcement steel, which dominate the embodied carbon profile of such buildings.

In contrast, adaptive reuse projects demonstrate significantly lower embodied carbon values, typically ranging between 300–500 $kgCO_2e/m^2$. This reduction can be attributed to the retention of existing structural components, which eliminates the need for new material production for major load-bearing elements. Since structural systems contribute the largest share of embodied carbon, their preservation directly reduces overall emissions.

The analysis indicates that the degree of carbon reduction is strongly influenced by the structural retention ratio. In scenarios where approximately 30–50% of the structural system is retained, embodied carbon reductions of around 30–40% are observed. In cases with higher levels of retention, exceeding 50–60%, reductions can approach or exceed 50%. This demonstrates that structural retention functions as the primary variable influencing embodied carbon outcomes.

However, adaptive reuse does not eliminate embodied emissions entirely. Retrofit interventions, including façade upgrades, interior modifications, and mechanical system integration, introduce additional materials and associated emissions. While these components contribute to the total embodied carbon, their impact is relatively lower compared to primary structural systems.

The results also highlight the importance of early-stage design decisions. Decisions related to demolition, structural retention, and retrofit intensity significantly influence the overall carbon performance of a project. Projects that prioritize maximum retention of structural systems consistently demonstrate lower embodied carbon intensities compared to those involving extensive reconstruction.

Overall, the findings confirm that adaptive reuse provides a measurable carbon advantage over new construction within the same typological and climatic context. This reinforces the role of reuse strategies in reducing upfront emissions in the building sector.

Building Type	Embodied Carbon ($kgCO_2e/m^2$)	Reduction
New Construction	450–750	—
Adaptive Reuse	300–500	30–50%

5. Discussion

The findings highlight the potential of adaptive reuse as a strategy for reducing embodied carbon in the built environment. In rapidly urbanising cities such as Bengaluru, redevelopment practices often prioritize new construction, leading to increased material demand and higher emissions.

Adaptive reuse offers an alternative approach that aligns development with environmental considerations. By retaining structural systems, it reduces reliance on carbon-intensive materials and minimizes construction waste.

From a design perspective, the study emphasizes the importance of incorporating lifecycle assessment into early decision-making processes. Architects and planners must evaluate both operational and embodied carbon when selecting development strategies.

At the policy level, the absence of embodied carbon regulation represents a critical gap. Integrating embodied carbon metrics into building codes could support more sustainable construction practices.

The study also highlights the need for improved data transparency in the construction sector. Greater availability of material quantity data would enhance the accuracy of embodied carbon assessments.

6. Conclusion

This study demonstrates that adaptive reuse can significantly reduce upfront embodied carbon in commercial buildings. By retaining structural systems and reducing material demand, adaptive reuse achieves lower carbon intensities compared to new construction.

The findings indicate potential reductions of approximately 30–50%, depending on the level of structural retention. These results support the integration of adaptive reuse into sustainable development strategies.

Future research should focus on detailed material quantification and project-specific lifecycle assessment to improve accuracy and reliability. The study contributes to the growing body of research on embodied carbon in the Indian context and highlights the importance of lifecycle thinking in architectural practice.

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