LIFE CYCLE ASSESSMENT OF STRUCTURAL MATERIAL REUSE IN ON-SITE PRESERVATION OF A CONCRETE STRUCTURE WITH TIMBER ADDITIONS

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ABSTRAC

Background and aim: The construction industry contributes approximately 19% of global greenhouse gas (GHG) emissions and accounts for one-third of worldwide energy consumption, underscoring its pivotal role in addressing climate change. This study evaluates the environmental impact of preserving an existing concrete structure versus constructing a new one with cross-laminated timber (CLT) or virgin concrete.

Methods and data: The effectiveness of environmental comparison in mitigating carbon emissions and reducing resource consumption is investigated through a comparative lifecycle analysis of reuse and replacement scenarios. Utilizing the Life Cycle Assessment (LCA) framework, three scenarios were analysed: (1) preserving existing concrete floors on-site and adding two cross-laminated timber (CLT) extensions, (2) demolishing the existing concrete structure to construct an entirely new five story building using CLT, and (3) demolishing and constructing a new five story structure with cast-in-place virgin concrete. The analysis comprehensively quantifies the Global Warming Potential (GWP) across the production, operational, and end-of-life stages.

Findings: Results demonstrate that reusing existing concrete floors reduces approximately 40 kg CO_2e/m^2 gross floor area compared to a new timber construction and 121 kg CO_2e/m^2 tons compared to new concrete construction.

Theoretical/practical/societal implications: The results highlight the environmental benefits of implementing circular economy principles into construction practices.

Keywords: Life Cycle Assessment, concrete reuse, cross-laminated timber, circular economy, carbon emissions.

1 INTRODUCTION

The construction industry is a cornerstone of economic and infrastructure development. However, it significantly contributes to global greenhouse gas (GHG) emissions and resource consumption, accounting for approximately one-third of global energy use (Kumar & Zhang, 2024). Boverket (2023) reports that the construction and real estate industries account for 21% of Sweden's annual CO_2 emissions, highlighting their critical role in achieving national climate objectives. Addressing these challenges through sustainable material usage can reduce emissions and resource depletion, particularly amid growing infrastructure demands (Akan, Dhavale & Sarkis, 2017). Yet, balancing economic growth with environmental sustainability remains complex, especially when transitioning to low-carbon economies. As the largest consumer of natural resources, the Architecture, Engineering, and Construction (AEC) sector plays a critical role in ecological sustainability. Climate change, a pressing 21st-century challenge, underscores the urgency of action, with Sustainable Development Goal (SDG) 13 emphasizing climate mitigation (Magazzino et al., 2022). Transitioning to a circular economy that optimizes resource use, minimizes waste, and reduces environmental impacts across material lifecycles offers a potential pathway. However, technological, institutional, market, and cultural barriers inder this shift (Grafström & Aasma, 2021). Moving from a linear

https://doi.org/10.52202/080684-0008

"take, make, dispose" model to a circular framework based on recycling and reuse is imperative (Elisha, 2020).

Initiatives to reduce environmental impact assessment of building materials have been recently introduced in EU (EU 2024). The EU Directive on energy performance of buildings (recast) emphasised measures to reduce the whole life-cycle greenhouse gas (GHG) emissions of buildings including material production, construction, operation, renovation and end of life stages. In Sweden, the climate declaration of buildings regulation (Boverket 2020) requires assessment of the carbon footprint of new buildings.

This study examines the environmental implications of adopting circular economy principles in the construction sector, focusing on the structural materials of concrete, steel, and cross-laminated timber (CLT). Specifically, the research addresses the optimization and reuse solution for the “Lumi” project, a five-story office building of 21 000 m^2 gross floor area in Uppsala, Sweden. Three stories of an old building are reused and CLT is used to construct two additional stories. Due to the structural limitations of the pre-existing foundation, constructing a large and heavy structure, such as one utilizing cast-in-place concrete, was deemed unfeasible. Assessing the environmental impact of structural systems, including cast-in-place concrete and CLT, is pivotal for advancing sustainable construction practices and addressing climate-related challenges.

The study focuses on three distinct scenarios to determine the option with the lowest environmental impact:

- **Scenario 1:** Retain three concrete floors and add two cross-laminated timber (CLT) floors.
- **Scenario 2:** Demolish concrete floors and construct a new five-story CLT building.
- **Scenario 3:** Demolish concrete floors and construct a new five-story concrete building.

Figure 1 illustrates the building and floors. Scenarios 2 and 3 necessitate the complete demolition of the concrete structure and the construction of an entirely new building.

The study examines greenhouse gas emissions, quantified in terms of carbon dioxide equivalents (CO-eq), to evaluate each scenario's environmental performance.

2 LITERATURE REVIEW

In the European Union, more than 20% of residential buildings were constructed before 1945 and are now approaching the end of their expected lifespans. This situation necessitates either the renovation or demolition of these structures (Czarnecki & Rudner, 2023). When decommissioning old buildings, approximately 70% of the waste from high-rise buildings has the potential to be reused or recycled (Umar, Shafiq, & Ahmad, 2020). Adopting a circular economy approach in construction and demolition waste management can offer both environmental and economic advantages. However, the sustainability of such efforts depends on site-specific factors including the type of material, building components, transportation distances, and the economic and political context (Ghisellini et al., 2017).

A recent report by the Swedish board of housing lists the typical climatic impact of different parts of buildings by focusing on phases A1 to A5 of the building life cycle (Malmqvist, T 2023). The findings reveal that the foundation and load bearing structure are the most significant contributors to the climate impact, often accounting for more than half of the emissions. This underscores the importance in efforts to reduce emissions from structural material. Conversely, energy usage and structural completeness contribute less to the impact of climate change, indicating opportunities for targeted improvements.

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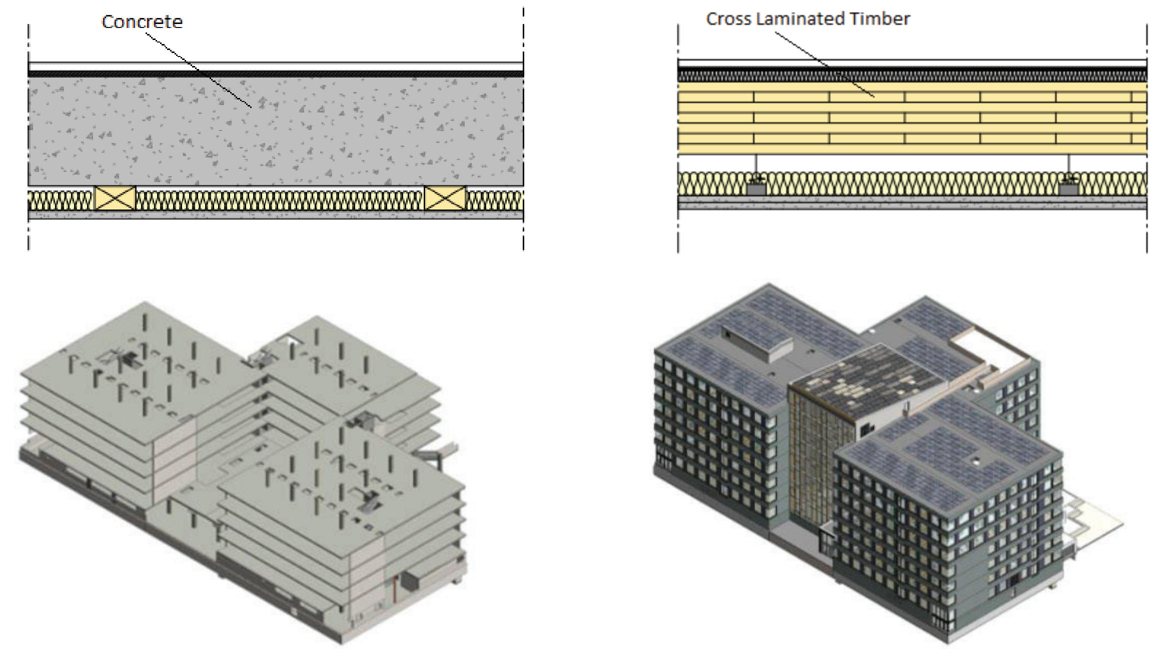

Figure 1: Above: Illustration of concrete and CLT floors Below: Illustrations of three retained concrete floors and the completed building with two additional cross-laminated timber (CLT) floors (scenario 1).

These results emphasize the critical need for life cycle assessment and material optimization to foster sustainable construction practices and achieve long-term ecological benefits.

Concrete is the most common material in building foundations and load bearing structures. The environmental consequences of concrete production are profound, primarily due to the carbon-intensive nature of cement manufacturing, a critical concrete component. Cement production, predominantly driven by the calcination of limestone, is responsible for approximately 8% of global CO_2 emissions, presenting a formidable challenge for climate change mitigation (Amran et al., 2022). Accelerating decarbonization and implementing improved solutions are imperative for achieving net-zero emissions, particularly in addressing the structural and foundational demands of the construction industry (Amran et al., 2022). As an example, design for deconstruction (DfD) offers environmental benefits 1.8 to 2.8 times greater than those of recycled aggregate concrete (RAC) (Xia et al., 2020). Life cycle assessment (LCA) models are essential in establishing sustainable cement standards. Terán-Cuadrado et al. (2024) underscore the significance of supplementary cementitious materials (SCMs), functional units, and supply chain dynamics in enhancing the sustainability of blended cement. Concrete production involves energy-intensive processes, including raw material extraction and high-temperature kiln operations, exacerbating its environmental footprint (Boakye et al., 2024). Furthermore, the environmental impact of concrete extends to its usage and disposal phases. Although concrete is highly durable, demolishing concrete structures generates considerable waste, much of which is downcycled or landfilled. While carbonation during its lifecycle absorbs a portion of CO_2, this compensates for only a fraction of the emissions generated during production (Alhawat et al., 2022).

Timber is distinguished by its renewable nature and carbon-sequestering properties. It acts as a carbon sink during its growth phase, capturing atmospheric CO. Life cycle assessment studies consistently indicate that timber exhibits a lower Global Warming Potential (GWP) than concrete, particularly during the production and construction phases. Its lightweight nature further contributes to reduced transportation emissions and enhanced construction efficiency. Duan et al. (2022) report that, despite the higher embodied energy of mass timber, it achieves 43% lower greenhouse gas (GHG) emissions than reinforced concrete (RC) (Duan et al., 2022). However, the ecological benefits of timber are contingent upon sustainable forestry practices. Unsustainable logging can result in deforestation, biodiversity loss, and carbon release, significantly undermining timber's advantages. Deforestation accounts for approximately 15% of global GHG emissions, contributing substantially to climate change (Kumar et al., 2022). Innovations such as cross-laminated timber (CLT) enhance timber's potential for construction while retaining its environmental benefits. Younis and Dodoo (2022) highlight the advantages of CLT, including a low carbon footprint, high strength-to-weight ratio, and ease of installation (Younis & Dodoo, 2022). A smart combination of CLT and the preserved existing concrete structure was used in the Lumi case. A

https://doi.org/10.52202/080684-0008

heavier structure than CLT would not have allowed the reuse of the three floors from the decommissioned structure on-site. Reusing concrete offers an avenue for reducing emissions associated with raw material extraction, cement production, and waste disposal.

3 METHODOLOGY

This study systematically quantifies the Global Warming Potential (GWP) of building constructions over the lifecycle, which includes raw material extraction, manufacturing and end-of-life disposal, using Life Cycle Assessment (LCA). Expressed in carbon dioxide equivalents (CO_2e), GWP standardizes the radiative forcing effects of various greenhouse gases into a single measure, thus enabling a scientifically robust evaluation of climate impact. Given its significant role in sustainability assessments, this study prioritizes GWP as the main environmental impact category when comparing structural alternatives. The analysis adheres to the EN 15978 standard (CEN (2011)) which defined the lifecycle phases as material manufacturing (A1–A3), construction processes (A4–A5), operational use (B1–B7), and end-of-life considerations (C1–C4). The LCA ensured a robust, systematic, and objective environmental performance evaluation by incorporating all lifecycle stages, as illustrated in Figure 2. This study comprehensively evaluated greenhouse gas emissions associated with four structural material scenarios over a 100-year lifecycle and defines 1 m² of gross floor area (GFA) per residential unit as the functional unit. This clear definition ensures methodological consistency in the Life Cycle Assessment (LCA) and enables comparability between the construction scenarios analyzed.
Operational energy and maintenance were excluded to focus exclusively on material-related emissions in a similar way to the Swedish climate declaration of buildings regulation. But in contract to the regulations, this study only included the load-bearing structure excluding foundation and roof etc.

The analysis was structured across three key lifecycle stages, as defined below:

- Phases A1–A5: Encompassing raw material extraction, production, transportation, and construction activities.
- Phase B: Addressing materials' energy-free durability and longevity during the operational phase.
- Phases C1–C4: Covering end-of-life processes, including demolition, waste management, recycling, and disposal.

3.1 DATA COLLECTION

The data collection within the study incorporates both primary and secondary sources to ensure precision, reliability, and standardization in assessing environmental impacts. The study includes:

- Primary Data: Lumi project structural design and material amounts.
- Secondary data: sources that include emission factors and material attributes from EPDs, literature, and industry sources like OneClick LCA.
- Additional inputs: Transportation distances and construction activities with fuel usage and emission factors.

3.2 CALCULATION OF GWP

Each material's GWP was calculated

- Material Inventory Assessment: Quantify materials utilized.
- Lifecycle Phase Assessment: Assess emissions throughout production (A1-A3), construction (A4-A5), use (B1-7), and end-of-life (C1-C4) stages.
- Verify GWP emission factors from EPDs for emission factor application.
- End-of-Life Considerations: Assess emissions from demolition, recycling, and material reuse credits.
- Results Aggregation: Each material's total phase emissions.

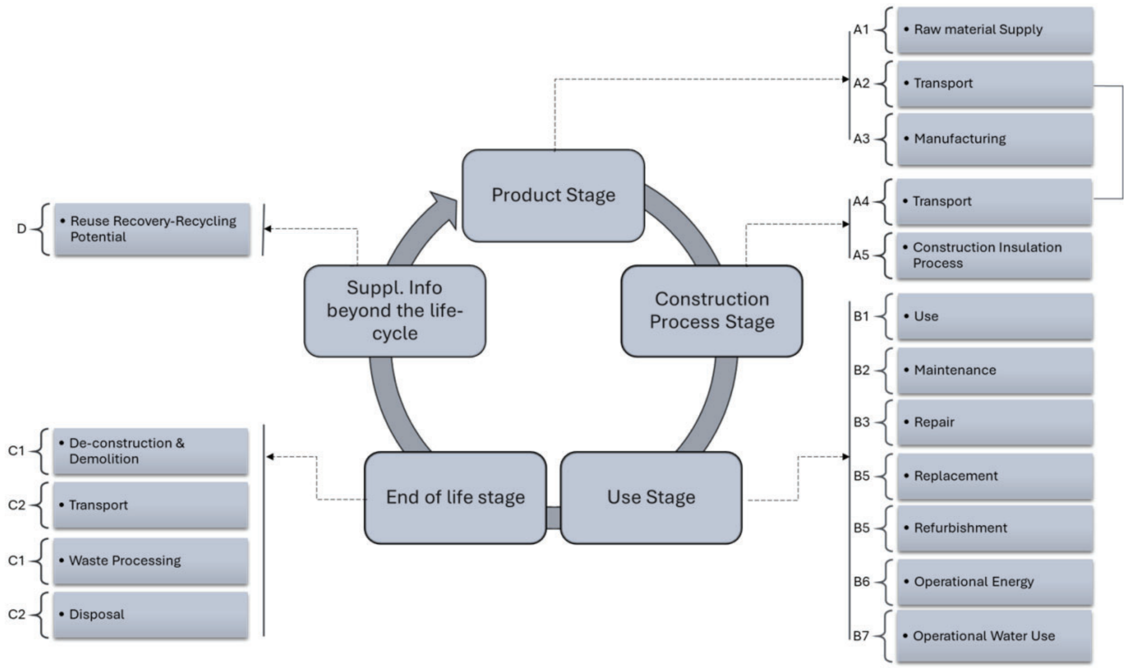

Figure 2: Life Cycle Stages in Construction and Their Environmental Impact Considerations

4 RESULTS & DISCUSSION

An analysis of the Global Warming Potential (GWP) of three structural alternatives revealed significant differences in environmental performance, expressed in kg CO_2e/m^2 gross floor area (Figure 3). Among the structures evaluated, Scenario 1, a preserved concrete structure with two added stories in CLT demonstrated the lowest GWP, calculated at 36 kg CO_2e/m^2, representing a 77% reduction compared to Scenario 3, a building with virgin concrete, which has a GWP of 157 kg CO_2e/m^2. This substantial reduction of 121 kg CO_2e/m^2, or a total of 2,800 tons $CO_2$for the whole building, was attributed to eliminating energy-intensive processes such as raw material extraction and cement manufacturing during life cycle stages A1–A3. Despite its widespread use, versatility, and durability, standard concrete's high environmental impact made it less suitable for sustainable construction practices. By reusing existing materials, the demand for new cement production was almost nullified, thereby mitigating emissions.

A complete five story timber construction (scenario 2), with a GWP of 76 kg CO_2e/m^2, offers a 52% reduction in emissions compared to standard concrete, resulting in an absolute reduction of 81 kg CO_2e/m^2. Even though the GWP assessments of timber do not account for biogenic carbon storage, which would further enhance its ecological benefits, timber provides a more sustainable alternative to standard concrete. However, the carbon savings with timber (Scenario 2) compared to standard concrete (Scenario 3) were less substantial than those achieved by reusing an existing concrete structure (Scenario 1). Moreover, current GWP assessments of timber do not account for biogenic carbon storage, which would further enhance its ecological benefits. While Scenario 2, timber, provides a more sustainable alternative to Scenario 3, standard concrete, its carbon savings were less substantial than those achieved by Scenario 1, reusing an existing concrete structure.

A comparison between preserved concrete structures on-site and new timber structures further highlights the superior environmental performance of reused concrete. With an additional reduction of 40 kg CO_2e/m^2 compared to timber (76 kg CO_2e/m^2 for timber versus 36 kg CO_2e/m^2 for reused concrete), reused concrete

https://doi.org/10.52202/080684-0008

demonstrates a greater capacity to minimize carbon emissions. For the whole building the reduction amounts to 1,800 tons CO_2. These findings underscore the critical role of material reuse in advancing sustainable construction practices and reducing the climate impact of the built environment. Although timber was a viable low-carbon alternative to standard concrete, reused concrete provides the most significant reductions in GWP, aligning more effectively with circular economy principles and sustainable development. In practice, the reuse of structural components not only reduces embodied emissions but also preserves the urban fabric and cultural value of existing architecture—providing social and aesthetic benefits alongside environmental gains.

The product stage represents the dominant share of the life cycle impacts in Scenario 3 with a concrete construction. As we introduce more timber the end-of-life stage becomes a more notable contribution to the building's overall environmental effects.

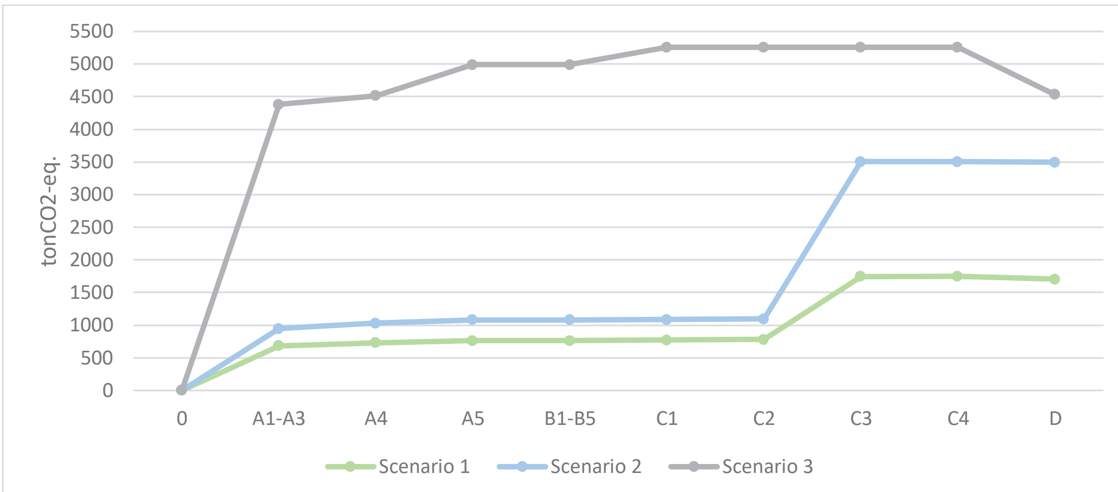

Figure 3: Comparative Analysis of Global Warming Potential (GWP) Across Lifecycle Phases for All Scenarios Over 100 Years.

This study expands beyond concrete to encompass cross-laminated timber (CLT), enhancing Life Cycle Assessment (LCA) by exploring material reuse in rehabilitation and new construction. Unlike other studies, such as De Wolf et al. (2020), which primarily focus on specific material lifecycles, this research integrates reuse techniques across various structural components. Incorporating an estimated building lifetime and correlating $kgCO_2e/m^2$ annually will further refine the assessment by providing a more accurate indication of long-term environmental impact.

4.1 CHALLENGES AND FUTURE RESEARCH

Despite promising outcomes, the study had limitations. Regional differences in material availability and transportation constraints limit the generalizability of the results. Future research could address these gaps by employing multi-impact assessments, examining reused concrete's long-term durability and cost-effectiveness, and incorporating biogenic carbon storage in timber life cycle evaluations. These advancements would aid in establishing evidence-based, sustainable construction methods by enhancing the understanding of material performance. While reusing materials offers significant environmental benefits, various practical and financial constraints impede its widespread acceptance. Reuse is often less economically viable than traditional construction due to high labor costs associated with demolition, sorting, and processing recycled materials, which typically outweigh any potential savings. Additionally, strict testing and certification requirements create further financial and logistical challenges. Other obstacles include transportation, on-site storage, and integrating salvaged components into new projects. Additional constraints on implementation involve limited market demand and the lack of consistent regulations. Future research should explore legislative incentives, streamlined regulatory frameworks, and improvements in modular design to boost cost-effectiveness and scalability in circular construction.

5 CONCLUSIONS

This study demonstrates that circular economy practices in the building sector, such as reusing structural materials, can significantly benefit the environment. The research evaluates three structural scenarios one utilizing an existing concrete structure on-site, one involving new cross-laminated timber (CLT) and the last virgin concrete—to assess their Global Warming Potential (GWP). Reusing the existing concrete structure and adding two CLT stories saves around 40 kg CO_2e/m^2 compared to a new CLT construction and 121 kg CO_2e/m^2 compared to a new concrete construction, effectively reducing greenhouse gas emissions. This emphasizes the environmental advantages of extending the lifecycle of existing materials while minimizing resource extraction and processing. Lifecycle emissions are consistently lower for scenarios involving reused concrete and new CLT than traditional concrete buildings, with reused concrete emerging as the most sustainable option. These findings highlight the critical role of material reuse in improving construction sustainability and reducing environmental impacts while acknowledging the practical challenges.

In conclusion, the synergy between structural reuse and renewable materials offers a robust pathway for reducing embodied carbon, particularly in the renovation and densification of existing urban areas. With strategic planning, the construction industry can shift from linear consumption models toward circular systems that prioritize longevity, adaptability, and climate resilience. Future work should continue to refine these assessments, scale demonstration projects, and embed circularity in mainstream architectural and engineering practices.

This study provides valuable insights for developing policies and strategies that align with global climate mitigation targets. Emphasizing resource efficiency and realistic approaches to lifetime emission reduction contributes to advancing the transition to low-carbon economies and promoting sustainable building practices.

ACKNOWLEDGEMENTS

The authors thank the Swedish Energy Agency for financial contributions to this study (grant P2023-01473).

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