

Comparison of mass timber structure and RC structure with regard to sustainability by life cycle assessment

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Abstract. Since the 18th-century Industrial Revolution, high-rise have played a crucial role in addressing urbanization challenges, remaining a primary solution for urban living. However, this architectural advancement has also contributed to environmental decline. Presently, steel and concrete stand out as the predominant materials for high-rise construction, with well-documented significant carbon emissions. This paper delves into the potential of timber as an environmentally friendly alternative in high-rise construction to address such environmental concerns. Furthermore, it examines the impact of these structures on land load. The paper conducts a comprehensive review of life cycle assessment (LCA) studies and offers a comparative analysis of the climate change impacts associated with timber versus conventional materials like reinforced concrete (RC), underscoring the urgent need for sustainable development in the vertical expansion of our cities. The findings demonstrate that both the mass and carbon emissions of high-rise timber structures, in comparison to RC structures, can be reduced by approximately half. The paper aims to underscore the benefits of timber in comparison to conventional reinforced concrete methods, thereby informing material selection in favor of sustainable urban development.

Keywords: Life cycle assessment, timber structure, high-rise building, greenhouse gas, climate change impact.

1. Introduction

The construction industry has become a major source of atmospheric CO₂ emissions, playing a substantial role in driving human-induced climate change. As per the International Energy Agency (IEA), in 2018, the building and construction industry accounted for a substantial 36% of the global final energy consumption, which contributed to a notable 39% of all energy and process-related carbon dioxide (CO₂) emissions worldwide. Within this context, it's important to highlight that a significant portion, amounting to 11%, of these emissions was directly attributable to the manufacturing of various key materials in construction and building industries such as steel, cement, and glass production [1].

Heightening population density, expanding urbanization and land shortage has increase the need of high-rise building. Estimates suggest that by the year 2050, around 70% of the world's population will reside in urban region, with trends of population increase and urban migration, leading to an expansion of vertical housing [2].

Furthermore, The Intergovernmental Panel on Climate Change (IPCC) has verified that in 2010,

buildings constituted 35% of the world's overall energy consumption and were responsible for 19% of energy-related greenhouse gas emissions [3]. If we continue with the current practices to meet our needs, this energy consumption and associated emissions may increase twofold or even threefold by 2050 [3]. The reduction of energy consumption and the mitigation of climate change effects from buildings are regarded as a vital step in mitigating climate changes by IPCC [3]. To achieve carbon neutrality by the year 2050, it is essential to ensure that every newly constructed building, as well as a substantial portion, specifically 20%, of the existing building infrastructure, achieves zero-carbon status by the year 2030. This ambitious objective demands a significant transformation in contemporary construction methods and the retrofitting of a considerable segment of current structures to meet rigorous zero-carbon criteria within the next decade [4].

Timber, as a construction material, offers distinct advantages over conventional high-rise building construction materials such as steel and reinforced concrete (RC). Research revealed that augmenting timber consumption by 17% can lead to an impressive decrease of carbon emissions by 20% from construction materials [5]. Timber is renewable and boasts a naturally low carbon footprint, contributing minimally to greenhouse gas emissions during its production and utilization. This stands in contrast to steel and RC, which are associated with higher carbon emissions due to their energy-intensive manufacturing processes [6].

This study presents a thorough review, comparison, and analysis of the structural components required for the construction of high-rise buildings of various heights, focusing on the use of both RC and timber as primary materials. A detailed Life Cycle Assessment (LCA) of each material is conducted to ascertain their environmental impacts. The assessment is designed to highlight the comparative environmental and practical advantages of timber against the traditional RC approach, thus guiding the choice of structural materials towards sustainable urban development.

The paper supplements its analysis by acknowledging the global discrepancies in defining what constitutes a high-rise or tall building, based either on the structure's height in meters or its number of floors. For this discussion, the definition of a high-rise aligns with the guidelines set by The Council on Tall Buildings and Urban Habitat (CTBUH), which identifies high-rises as buildings measuring 35 to 100 meters in height, typically equating to about 12 to 40 stories [7]. This uniform definition guarantees that the investigation of structural materials remains pertinent and applicable across the international landscape of high-rise architecture. In line with these standards, the research benchmarks a spectrum of buildings ranging from 12 to 21 stories.

2. Life Cycle Assessment

LCA is a methodical approach for evaluating the ecological effects associated with each phase in the lifespan of a product, from the initial gathering of its foundational components to its ultimate termination—a concept often termed as cradle to grave. This approach, established as a standard by the International Organization for Standardization in ISO 14040 [8], provides a consistent framework for assessment, as depicted in figure 1, which ensures methodological consistency and comparability across studies.

Figure 2 illustrates the four separate phases constituting life span of a building, from which environmental effects originate. These phases include material production (A1-A3) and construction (A4-A5), the operational lifespan (B1-B7), end of life (C1-C4), and potential advantages and loads that extend beyond the system boundary (D), as per the European Standard EN 15978 [9]. Through the examination of this assessment, we can comprehend and minimize the environmental impacts that span the entire lifecycle of construction materials—including manufacturing, transportation, construction, operation, maintenance, and the final demolition and waste management of the building etc.

In the quest to reduce the environmental footprint of the construction industry, LCA is becoming an indispensable tool. Recognized increasingly for its importance in evaluating and mitigating the ecological impacts of construction materials and methods, LCA is gaining traction across the sector. It encompasses a building's journey from inception to demolition, offering a comprehensive and systematic approach. This method not only provides a wide-ranging perspective but also ensures a thorough consideration of every aspect. By offering an integrated evaluation of a building's

environmental impact, LCA stands as a key concept in modern green building research and assessment, emphasizing the significance of sustainable practices in construction [10].

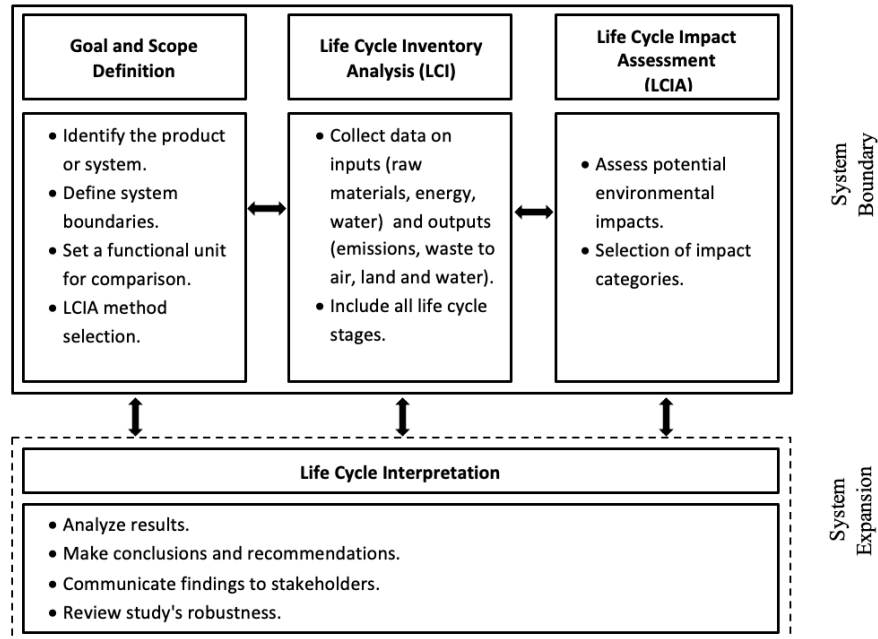


Figure 1. LCA Framework based on ISO 14040 [8].

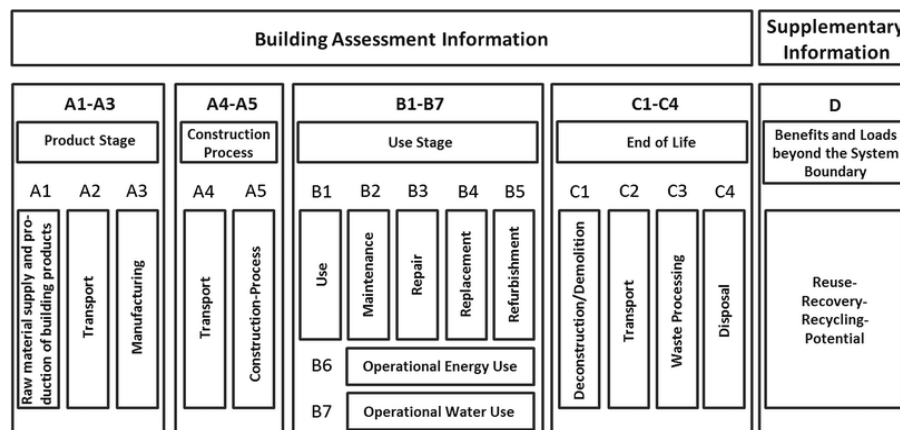


Figure 2. LCA modules for comprehensive building evaluation from inception to end-of-life as per the EN 15978 standard [9].

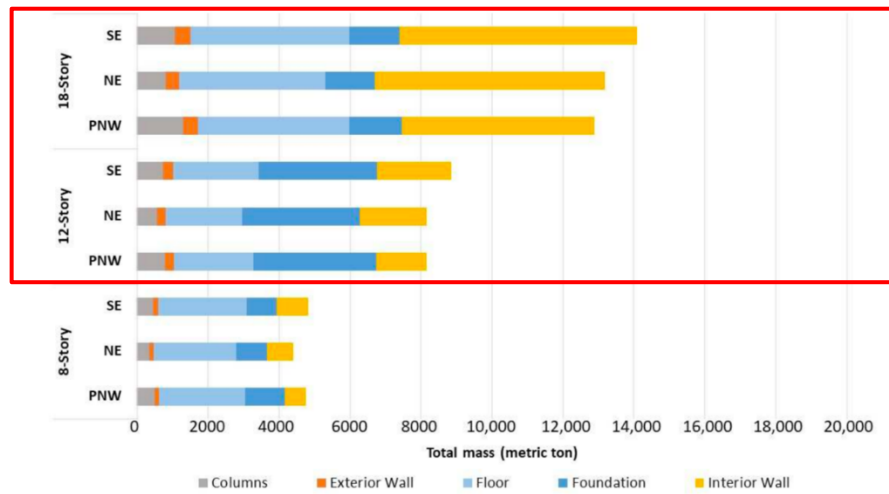
3. Mass Timber vs. Reinforced Concrete Building

Puettmann et al. [11] explored the environmental advantages of using mass timber (MT) for building projects, in contrast to the environmental impacts of conventional concrete structures, with a focus on the release of greenhouse gases from the start of the material life cycle to the construction phase. This evaluation included resource extraction (A1), transportation to the manufacturing site (A2), the manufacturing process (A3), delivery to the building location (A4), and the energy consumption during construction (A5).

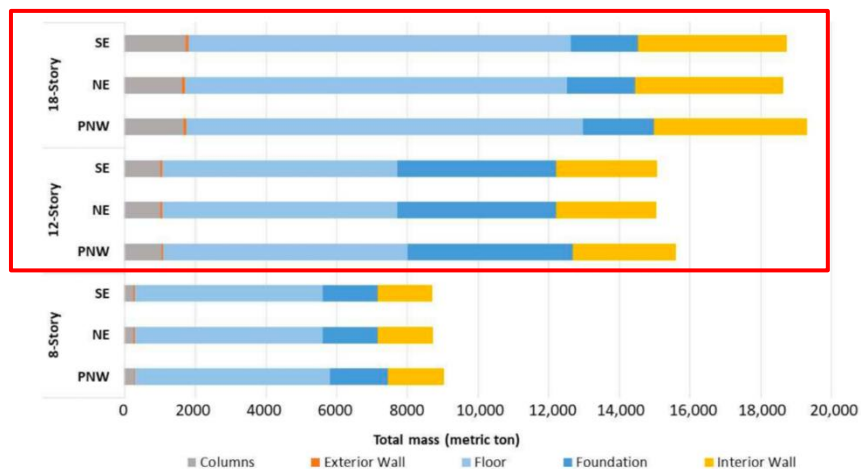
The study highlighted that implementing MT in the construction of buildings of various heights, particularly 8, 12, and 18 stories, in distinct United States locations—Seattle, Boston, and Atlanta—required certain assumptions about soil analysis for bearing capacity. The outcomes for the 12 and 18-story buildings, as documented by Puettmann et al., were of particular interest [11].

The research highlighted a notable reduction in the mass of buildings constructed with MT; specifically, a 12-story MT building weighs almost half as much as a RC structure. For buildings reaching 18 stories, MT structures are lighter by an estimated 2,500 metric tons, as shown in figure 3 [11]. The weight of high-rise buildings can negatively impact the environment; the greater the mass of the building, the more substantial the force exerted on the soil below. Constructing high-rises, particularly in regions with soft soil, may result in land subsidence—a scenario where the soil compacts and settles, causing the ground level to drop under the weight of large structures [12]. Additionally, large and heavy buildings necessitate deep and extensive foundations, potentially disrupting the land’s natural state, altering underground water tables, and changing the natural flow of groundwater [13].

Regarding the total embodied carbon from life cycle stages A1-A5, a 12-story wooden building emits 55-62% of the embodied carbon of an RC building. An 18-story MT structure emits 69-78% of that of an RC building, as shown in table 1, with variations primarily due to differences in transportation distances during the product stage (A2) [11].



(a) Mass of materials in mass timber buildings



(b) Mass of materials in concrete buildings

Figure 3. The mass of materials utilized in (a) mass timber and (b) concrete buildings with 8, 12, and 18 stories, situated in the Pacific Northwest (PNW), Northeast (NE), and Southeast (SE) areas of the U.S. [11].

Table 1. Embodied carbon totals across life cycle stages (A1–A5) for buildings made of mass timber and concrete. [11].

PNW Embodied Carbon kg CO ₂ e/m ²									
Building System		A1-A3		A4		A5		Total	
12-story	Mass timber building	139.2	88.5%	12.8	8.1%	5.3	3.4%	157.3	100.0%
	Concrete building	264.5	94.0%	6.3	2.2%	10.7	3.8%	281.4	100.0%
18-story	Mass timber building	146.1	87.3%	14.8	8.8%	6.5	3.9%	167.3	100.0%
	Concrete building	223.4	93.5%	5.3	2.2%	10.1	4.2%	238.9	100.0%
NE Embodied Carbon kg CO ₂ e /m ²									
		A1-A3		A4		A5		Total	
12-story	Mass timber building	121.4	86.1%	14.2	10.1%	5.3	3.8%	141.0	100.0%
	Concrete building	254.0	95.1%	3.1	1.2%	9.9	3.7%	267.0	100.0%
18-story	Mass timber building	130.0	87.2%	13.0	8.7%	6.1	4.1%	149.1	100.0%
	Concrete building	196.3	94.6%	2.6	1.2%	8.6	4.1%	207.4	100.0%
SE Embodied Carbon kg CO ₂ e/m ²									
		A1-A3		A4		A5		Total	
12-story	Mass timber building	144.0	90.8%	8.76	5.5%	5.81	3.7%	158.6	100.0%
	Concrete building	242.6	95.7%	1.12	0.4%	9.86	3.9%	253.5	100.0%
18-story	Mass timber building	157.2	91.4%	7.68	4.5%	7.09	4.1%	172.0	100.0%
	Concrete building	210.5	95.3%	0.96	0.4%	9.43	4.3%	220.9	100.0%

The study by Skullestad et al [3]. investigated reducing greenhouse gas (GHG) emissions in multi-storey structures by replacing steel and concrete with timber. the study omitted buildings of 3, 7, 12, and 21 storeys. This paper will concentrate on high-rise buildings; hence 3 and 7 storeys buildings are out of the scope of this paper. The comparison was based on identical load-bearing capacity, location, and wind speed, considering only materials required for the load-bearing structure and foundations.

The system boundaries were established from cradle-to-gate (A1-A3), including an analysis of advantages and burdens extending past the system boundary (D). Three distinct calculation approaches were used to assess LCA, Approach 1 involved calculating and multiplying material emission factors by the corresponding material quantities. Approach 2 added the Global Warming Potential of biogenic CO₂ (GWPbio) factors and considered concrete carbonation over the building's lifetime. Approach 3 took a consequential perspective, looking at impacts from reuse, recycling, and concrete carbonation after the end of life [3].

The study revealed that timber structures exhibit a substantially reduced impact on climate change and GHG emissions than RC structures. Timber buildings caused approximately 30-85% less climate change impact (CC) than RC buildings, a variance influenced by building heights and methodological approaches. When 90% of timber by-products and waste underwent incineration with heat recapture, GHG emissions reduction potentials increased. Consequential analysis showed that timber structures could result in negative CC, reducing CO₂-equivalent emissions by -140 to -235 kg per square meter depending on building height. This underscores timber buildings as a more sustainable construction option, especially for climate change mitigation [3].

4. Conclusion

In conclusion, the analysis reveals that mass timber structures significantly reduce the structural weight of high-rise buildings, offering an eco-friendlier alternative by halving the load exerted on the land

compared to traditional reinforced concrete buildings. This weight reduction is vital in the burgeoning construction of high-rises and the consequent environmental burden.

Although the CC impact may vary with the height of the building, mass timber consistently results in less CC impact than reinforced concrete in every method analyzed. This finding underscores the potential of mass timber as a more sustainable building material in terms of reducing CC impact, regardless of the building's height.

The study's limitations might include variations in regional factors that affect energy usage. In the cited research, thorough comparisons between buildings made of mass timber and those of reinforced concrete were carried out, ensuring these assessments were performed in identical geographical regions to keep the analysis consistent. Nonetheless, it's crucial to understand that the energy consumed in manufacturing and moving construction materials may vary across different areas. This variation results from differences in transportation distances and methods, implying that LCA for buildings might yield different outcomes depending on their specific locations.

Different soil conditions and geological characteristics can lead to variations in foundation requirements and the quantity of materials used. Geographic locations with erosive elements, such as maritime winds, may influence the durability of mass timber versus reinforced concrete. Therefore, further research into their respective life spans under varying environmental stressors is warranted. This additional research could provide more comprehensive insights into the long-term sustainability and resilience of these building materials in different geographical settings. Replacing reinforced concrete with timber in high-rise buildings is undeniably beneficial for the environment. This substitution significantly reduces the structural pressure on the land and greatly lowers carbon emissions. Nonetheless, the development of timber structures might be limited due to a lack of comprehensive legal and standard support. In many countries, existing building regulations may not adequately recognize the characteristics and advantages of timber, highlighting the need for further legislative and regulatory advancements to encourage the innovation and application of timber construction techniques. Consequently, it is essential for policymakers, architects, and engineers to collaborate in creating suitable building standards and norms for timber structures to facilitate the adoption and growth of this environmentally friendly building material.

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