



CARBON BENEFIT OF MODULAR MASS TIMBER:

A STUDY ON THE HORIZONTAL ELEMENTS

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Abstract

As the construction industry pursues low-carbon strategies, modular mass timber systems, particularly those using Cross-Laminated Timber (CLT), are emerging as viable alternatives to conventional framing. This study evaluates the environmental performance of CLT floor and ceiling systems compared to conventional lightwood joists in a modular construction context. Using Tally, a BIM-integrated life cycle assessment (LCA) tool, the research quantifies impacts across key categories including Global Warming Potential (GWP), energy use, and material efficiency. Results show that CLT offers 42% lower embodied carbon in the product stage, reduces on-site labor by 67%, and cuts construction-phase electricity use by over 60%. While some mid-stage impacts such as acidification are slightly higher for CLT, the overall life cycle performance is superior due to reduced material redundancy and prefabrication efficiency. The findings support CLT as a carbon-smart solution for volumetric modular housing and highlight the need for improved LCA tool accuracy and transport logistics in future studies.

Keywords: Modular Construction, Mass Timber, Carbon Sequestration, Sustainability, Embodied Carbon, Green Building., Tally

1.0 INTRODUCTION

The construction industry is a huge contributor of global carbon emissions accounting for approximately 37% of total CO₂ emissions ([UNEP, 2022](#)). These emissions are broadly categorized into operational carbon and embodied carbon (Ibn-Mohammed et al., 2013). While operational carbon has historically received significant attention due to its direct link to energy consumption, embodied carbon is becoming increasingly relevant as the industry shifts toward sustainable building practices (Jensen et al., 2020). Mass timber construction has emerged as a promising alternative to traditional building materials, offering the potential to significantly reduce embodied carbon emissions (Robati & Oldfield, 2022). Industrialized construction, providing time and labor costs saving by 40%, can address the crisis of affordable housing. Savings come from optimization, mass production, and faster delivery. Modular Construction, widely known as Industrialized Construction, provides carbon benefits due to faster and more efficient project delivery, with CO₂ emissions reductions ranging from 25% to 43% compared to site-built construction (Kouhirostami, 2023). Industrialized construction primarily includes two types, panelized and volumetric modular construction (VMC), where the majority of construction work is performed in a factory (Sadoughi et al., 2024). This study focuses on volumetric modular constructions. The conventional high-impact material and factory assembly will be optimized using cross-laminated timber panels. Utilizing mass timber increases the climate resiliency benefits by eliminating gypsum ceilings, storing biogenic carbon, and improving the durability (60-100 years) of mass timber, faster production, and biophilic interior design features. Modular and industrialized construction serve as both delivery and material strategies. When combined with engineered wood systems like CLT, they offer compounding benefits in efficiency and carbon reduction.

1.1 Operational Carbon & Embodied Carbon

Operational carbon refers to the greenhouse gas emissions generated during a building's use phase, primarily from energy consumption for heating, cooling, ventilation, and lighting. Mass timber, particularly Cross-Laminated Timber (CLT), enhances energy efficiency due to its superior thermal insulation and airtightness, making it an effective material for Passive House and net-zero energy buildings (Pan et al., 2022; Setter et al., 2019).

In contrast, embodied carbon accounts for the total emissions associated with material extraction, manufacturing, transportation, installation, and disposal, with traditional materials like concrete and steel being major contributors (Jackson & Brander, 2019; Liu & Leng, 2022). CLT presents a lower-carbon alternative by sequestering atmospheric CO₂ throughout its lifecycle, reducing the overall carbon footprint of buildings (Kwok et al., 2020). With advancements in engineered wood products such as Glulam and NLT, mass timber is emerging as a structurally viable and environmentally sustainable option for modern construction (Puettmann et al., 2021).

1.2 Goals and Objectives

This study aims to explore the environmental benefits of mass timber in volumetric modular construction through a Life Cycle Assessment (LCA) approach, with a focus on embodied carbon reductions. The objectives of this research are as follows:

1. Quantify the embodied carbon footprint of floor and ceiling systems using CLT compared to conventional joist framing.
2. Identify limitations of LCA tools such as Tally when modeling mass timber systems.

3. Provide data-driven recommendations to help policymakers, architects, and developers leverage CLT for carbon reduction in modular construction, particularly for affordable housing.

2.0 STRUCTURAL AND MATERIAL COMPARISON

Floor and ceiling systems vary in efficiency, load distribution, and material optimization. Conventional joist-based systems rely on closely spaced lumber joists and multiple components for load transfer, often requiring additional reinforcement for longer spans. In contrast, CLT panels offer two-way spanning capability, reducing material redundancy and simplifying construction. Prefabrication further enhances CLT's efficiency by minimizing waste and installation time.

2.1 Conventional Floor and Ceiling Systems (Joist-Based Construction)

Conventional floor and ceiling systems are typically composed of 2x8 SPF combined with plywood decking and gypsum ceiling boards. These systems require multiple components to effectively transfer loads, including blocking, fasteners, and adhesives. The load distribution in this construction method is unidirectional, relying on closely spaced joists set at 16 inches on center. Additional reinforcement is necessary to control deflection and vibration to maintain structural integrity over longer spans.

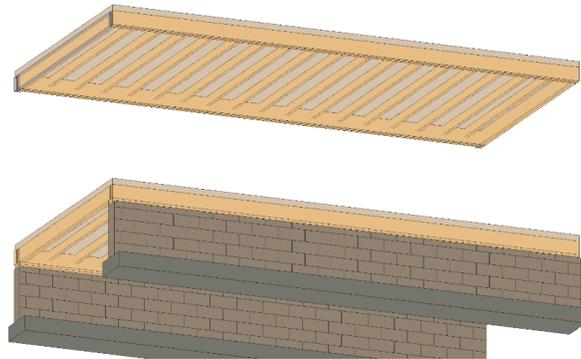


Figure 1.0 Conventional floor and ceiling joist system from Revit

2.2 Cross-Laminated Timber (CLT) Floor and Ceiling Systems

In contrast, cross-laminated timber (CLT) floor and ceiling systems utilize monolithic engineered wood panels that provide two-way spanning capability, which helps to reduce material redundancy. Eliminating the need for secondary structural elements, CLT simplifies construction and minimizes the number of required components. The material's high stiffness and favorable strength-to-weight ratio allow for larger spans while maintaining thinner sections. Additionally, the prefabrication process ensures high precision in manufacturing, which leads to reduced installation time and minimizes on-site material waste.

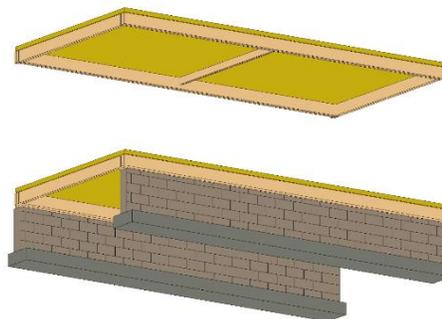


Figure 2.0 CLT floor and ceiling system from Revit

2.3 Challenges and Limitations of Using Tally for Building Life Cycle Assessment

Tally is a BIM-integrated LCA plug-in for Autodesk Revit that enables whole-building environmental assessment using the GaBi database and TRACI impact categories. Despite Tally's accessibility and utility within Revit, several critical challenges limit its broader application in high-level research, international projects, and rigorous sustainability reporting.

- Platform Restriction: Revit Dependency

Tally functions exclusively within Autodesk Revit, requiring a fully modeled and material-tagged BIM environment. This limits accessibility to firms and researchers using alternative modeling software.

- Limited EPD Integration

Tally operates with a closed material database that cannot import third-party Environmental Product Declarations (EPDs). Tally restricts users to generic material profiles.

- Embodied-Only Focus: No Operational Carbon Modules

Tally's analytical scope is restricted to product and end-of-life stages (Modules A1–A3, A4, B1, C1–C4, and D). It does not account for operational energy or water use (Modules B6 and B7), which are essential for comprehensive Whole Building Life Cycle Assessments (WBLCA).

- High Sensitivity to Model Quality

Effective LCA in Tally hinges on accurate material assignments and component modeling in Revit. Generic or unassigned elements default to “unclassified” and are excluded from calculations.

3.0 METHODOLOGY FOR LIFE CYCLE ASSESSMENT USING TALLY

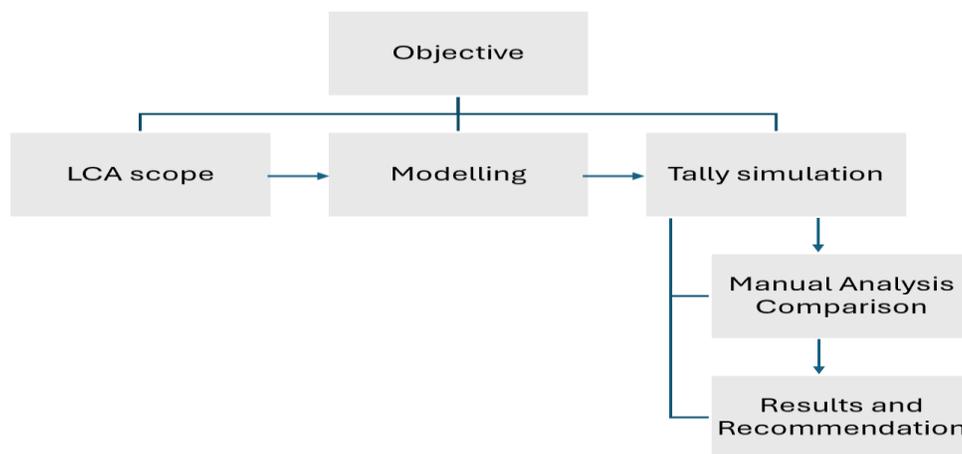


Figure 3.0 Research Methodology and Workflow

3.1 Study Approach and Framework

This study employs a Life Cycle Assessment (LCA) approach using the Tally plug-in for Revit to evaluate the environmental impact of a conceptual building design. The assessment follows the standard LCA framework outlined in ISO 14040/14044, ensuring a structured and repeatable methodology. The process consists of defining the study scope, collecting life cycle inventory data, performing an impact assessment, and interpreting results (International Organization for Standardization (ISO), 2007).

The focus is on quantifying the environmental impacts of materials using Tally's built-in database, which is aligned with the GaBi Life Cycle Assessment database.

3.2 Scope Definition

The goal of the LCA was to assess the environmental impacts of the building elements during the product and construction stages of its life cycle, with a focus on the environmental impacts of the elements in a modular mass timber structure. Special attention was given to wood-based materials, such as CLT and lumber, to evaluate their role in reducing embodied carbon.

The Life Cycle Stages, as developed per EN 15978 standards (CEN, 2011) cover the Product Stage, Construction Stage, Use Stage, End-of-Life Stage, and Module D. This Paper covers the Product Stage and Construction Stage only.

3.3 Building Components and Material Assignment

CLT elements were modeled as 5-ply panels (approx. 6.875" thick), constructed from Douglas Fir, with a 50-year service life. The conventional system used 2x8 SPF joists spaced at 16" o.c. Two separate models were created in Revit: one for CLT floor/ceiling and one for lightwood joist systems, each with material assignments performed independently in Tally.

Tally requires each building component to be assigned a specific material type for accurate impact calculations. The following elements were mapped within the software:

- **Floor and Ceiling** – Defined as **Cross-Laminated Timber (CLT)**, with detailed specifications on **wood type, density, service life, and finish requirements**.

3.4 Data Processing and Impact Assessment

Global warming potential (GWP) is the most relevant impact category to assess for carbon benefits, as it directly measures the contribution to climate change (Tait & Cheung, 2016). The Tally software was used to calculate the embodied carbon associated with each building component, considering the defined system boundaries and material specifications. Once materials were assigned, Tally processed the **Life Cycle Inventory (LCI) data** and computed environmental impacts based on the (TRACI 2.1 impact categories), including: Global Warming Potential (kg CO₂e), Ozone Depletion Potential (kg CFC-11 eq), Acidification (kg SO₂ eq), Eutrophication (kg N eq), Smog Formation (kg O₃ eq)

The software provided a **detailed breakdown of embodied impacts** across different material groups, highlighting the most significant contributors.

3.5 System Descriptions and Model Parameters

To facilitate a comparative life cycle assessment (LCA), two structural floor and ceiling systems were modeled in Revit and assessed using Tally. Both systems were designed to support an equivalent area and load, allowing a consistent environmental performance comparison.

Geometry and Modeled Area

- Modeled area: **276.4 ft² (25.68 m²)** floor and ceiling system
- Ceiling: standard flat ceiling under primary structure
- Height: **9 ft floor-to-ceiling**
- CLT panel system comprises 5-ply CLT, Douglas Fir, ~6.875 in. thick (175 mm)
- Assembly composition: CLT panels (load bearing), No floor finish, CLT panel ceiling
- Conventional Joist System consists of 21 joists (2x8 SPF @ 16" o.c.), dimensional lumber joists (2x8 SPF), plywood subfloor, gypsum ceiling board

4.0 RESULTS AND DISCUSSION

4.1 Life Cycle Assessment (LCA) Overview

This project integrates mass timber construction with advanced life cycle assessment (LCA) methodologies to evaluate its environmental impact. The analysis includes the cradle-to-gate Analysis. This section presents the key environmental performance results categorized by materials, transportation, labor, and other essential factors affecting the carbon footprint of the structure.

4.1.1 Inventory Analysis

Material Scope: This study evaluates and compares two distinct material systems used for floor and ceiling construction: Cross-Laminated Timber (CLT) and conventional stick-built assemblies.

The total surface area modeled for both floor and ceiling systems is 276.4 square feet per system.

The data for each system was obtained using a combination of Revit/Tally outputs and supplemental manual calculations.

4.2 Environmental Impact Assessment per Life Cycle Stage

This section presents a concise comparison of key environmental metrics between the CLT and joist-based systems across life cycle stages. Impacts are summarized for Global Warming Potential (GWP), acidification, energy use, and construction efficiency.

4.2.1 Material Impact Analysis

CLT systems offer significantly lower embodied carbon in the product stage (A1–A3), with a net GWP of **-3,655 kg CO₂eq**, compared to **-2,124 kg CO₂eq** for joists. The difference is due to CLT's monolithic structure and higher carbon sequestration capacity. CLT also has fewer components (no gypsum, less adhesive), which lowers emissions across impact categories.

4.2.2 Transportation Impact

Both systems assumed a transport range of 500 miles using diesel trucks. According to Tally's results:

- **CLT Transport (A4):** 77.79 kg CO₂eq
- **Joist Transport (A4):** 67.43 kg CO₂eq

While values appear similar, the slightly higher emissions for CLT are attributed to its heavier, consolidated panel format. These differences may become more pronounced with longer haul distances or higher load frequency.

4.2.3 Labor and Construction Efficiency

Construction energy use was estimated based on literature-derived labor rates and energy demand per square foot (RSMMeans):

Joist system has 0.111 hrs/ft², CLT: 0.037 hrs/ft² and the area of the model is 276.4 ft²

For Electricity Conversion: 1.5kWh per house source: [\(roi, 2023\)](#)

Table 1.0 Labor hours per square feet

System	Labor Time	Electricity Conversion	Final Electricity (kWh/m ²)
CLT	~0.037 hrs/ft ²	1.5 kWh per hour	~0.056 kWh/ft ²
Joist	~0.111 hrs/ft ²	1.5 kWh per hour	~0.167 kWh/ft ²

Table 2.0 Labor hours and electricity totals

System	Labor Hours Total	Electricity Total
CLT	0.037 × 276.4 = 10.23 hrs	0.056 × 276.4 = 15.48 kWh
Joist	0.111 × 276.4 = 30.68 hrs	0.167 × 276.4 = 46.16 kWh

These electricity values were entered into Tally as **on-site construction energy (A5)**. The results showed:

- **CLT On-site Energy GWP (A5):** ~77.79 kg CO₂eq
- **Joist On-site Energy GWP (A5):** ~67.43 kg CO₂eq

Despite higher installation efficiency for CLT, the emissions were slightly higher due to the U.S. average grid mix, which is sensitive to total electricity input; Source: [Decarbonizing America's power grid](#)

Environmental Impact Totals	Product Stage [A1-A3]	Construction Stage [A4-A5]	Use Stage [B2-B5]	End of Life Stage [C2-C4]	Module D [D]
Global Warming (kg CO ₂ eq)	-3,655	77.79	-534	2,844	434.6
Acidification (kg SO ₂ eq)	8.227	0.3369	17.51	10.18	-3.07
Eutrophication (kg Neq)	0.6544	0.02945	2.932	2.522	-0.1277
Smog Formation (kg O ₃ eq)	114.5	10.70	144.3	35.45	-37.2
Ozone Depletion (kg CFC-11eq)	1.332E-004	1.599E-011	1.310E-004	2.268E-011	-6.183E-009
Primary Energy (MJ)	41,114	1,171	40,646	1,558	-21,036
Non-renewable Energy (MJ)	14,098	1,125	15,394	1,464	-12,262
Renewable Energy (MJ)	27,015	46.13	25,251	93.37	-8,812

Figure 4.0 Summary of CLT and structural framing

Environmental Impact Totals	Product Stage [A1-A3]	Construction Stage [A4-A5]	Use Stage [B2-B5]	End of Life Stage [C2-C4]	Module D [D]
Global Warming (kg CO ₂ eq)	-2,124	67.43	-101	1,467	211.0
Acidification (kg SO ₂ eq)	2.016	0.2422	2.003	2.808	-1.23
Eutrophication (kg Neq)	1.302	0.02574	0.9076	0.2619	-0.05122
Smog Formation (kg O ₃ eq)	47.68	6.704	27.63	14.04	-15.3
Ozone Depletion (kg CFC-11eq)	1.358E-005	4.205E-011	8.116E-006	1.126E-011	-2.597E-009
Primary Energy (MJ)	13,580	1,100	7,445	816.7	-8,602
Non-renewable Energy (MJ)	5,512	1,020	3,996	765.4	-4,887
Renewable Energy (MJ)	8,067	79.70	3,449	51.30	-3,697

Figure 5.0 Summary of joist with structural framing

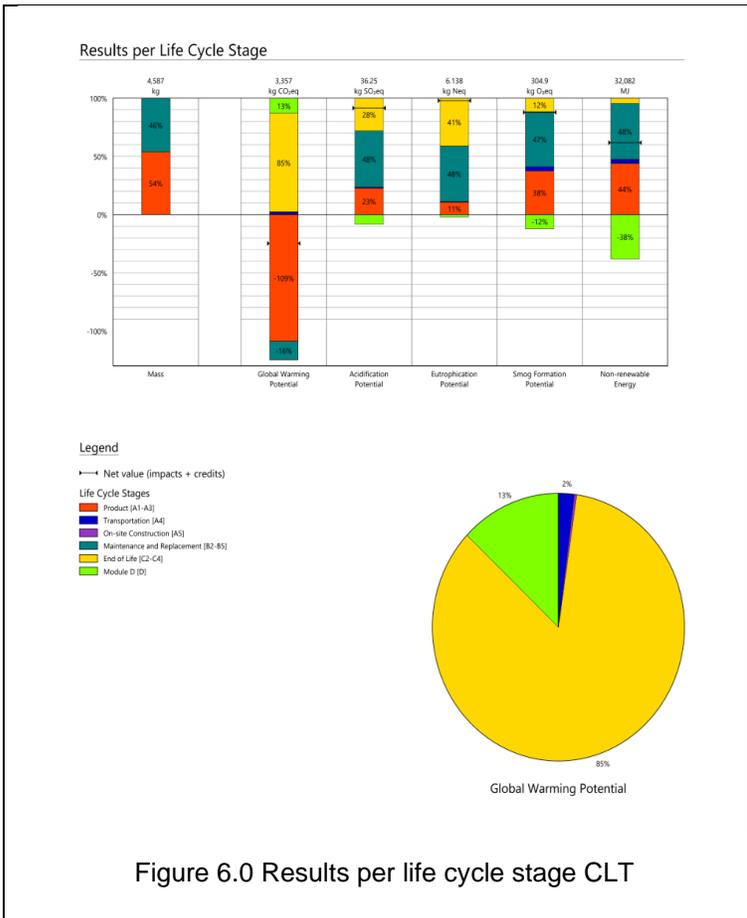


Figure 6.0 Results per life cycle stage CLT

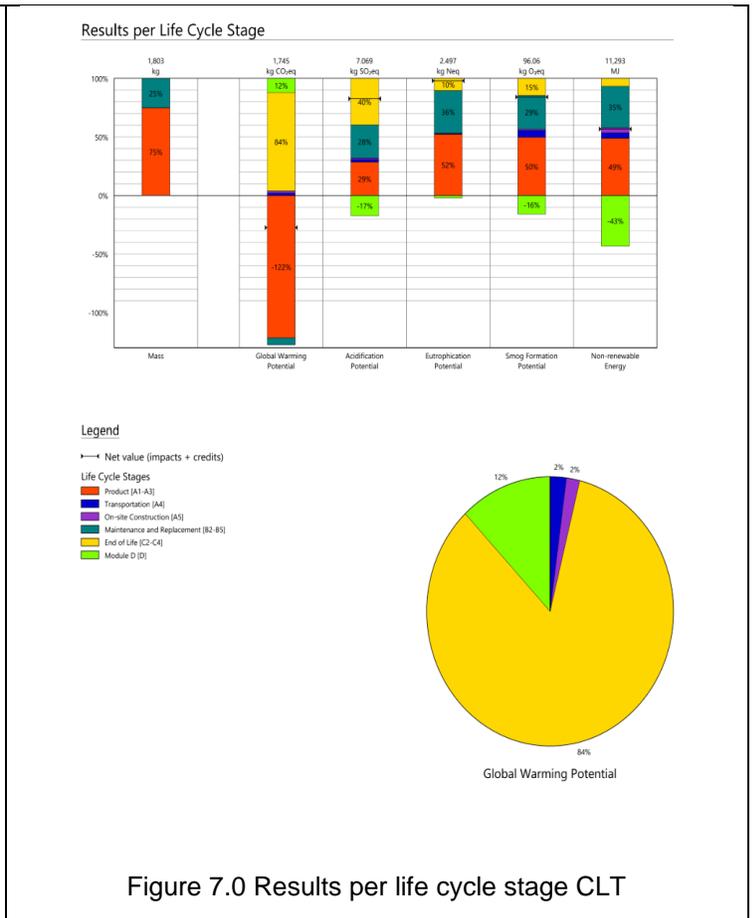


Figure 7.0 Results per life cycle stage CLT

4.3 Additional Environmental Impacts Beyond GWP

Although Global Warming Potential (GWP) remains the primary metric for assessing embodied carbon, other environmental categories presented in Figure 6 and Figure 7 were also analyzed to provide a more comprehensive understanding of the systems' sustainability performance.

- **Acidification (kg SO₂eq)**
CLT showed **higher acidification potential** during the product stage (**8.23 kg SO₂eq**) compared to the joist system (**2.02 kg SO₂eq**). This is largely attributed to upstream processes in engineered wood manufacturing, including adhesives and lamination treatments. However, CLT still maintains advantages during the construction and end-of-life stages due to reduced on-site chemical use.
- **Eutrophication (kg N eq)**
Eutrophication impact was higher in CLT (**0.65 kg Neq**) than joists (**1.30 kg Neq**) at the product stage, but CLT outperformed joists in later stages. Overall, the impact is modest in both systems and is typically driven by upstream electricity sources and material processing waste.
- **Smog Formation (kg O₃eq)**
CLT presented **greater smog-forming emissions** in total (**~114.5 kg O₃eq**) versus joists (**~47.68 kg O₃eq**) at the product stage. This difference is attributed to the more energy-intensive processing and gluing stages of CLT production. However, the smog potential per square meter was offset by CLT's efficient use of material and reduced on-site emissions.
- **Ozone Depletion Potential (kg CFC-11 eq)**
The ozone depletion impact remained extremely low for both systems across all stages. CLT had a slightly higher value due to manufacturing processes involving heat and resins, but the magnitude (on the order of 10⁻⁵ to 10⁻⁷) is negligible compared to GWP.

CLT systems show higher impacts in categories like acidification and smog formation at the product stage, their superior performance in material efficiency, reduced waste, and lower energy use during construction offsets many of these effects across the full life cycle.

4.3.1 Comparative Analysis of Embodied Carbon, Construction Energy, and Material Efficiency for CLT vs. Joist Floor Systems

Manual cross-checking of GWP values for selected assemblies was conducted using EPD data from EC3 and GaBi, confirming consistency with Tally's estimates within a 5% margin.

Table 3.0 Comparative analysis of carbon, energy and material efficiency

Category	CLT System	Joist System	Remarks
GWP (Product Stage A1–A3)	-3655 kg CO ₂ eq/m ²	-2124 kg CO ₂ eq/m ²	CLT sequesters more carbon due to monolithic engineered timber panels.
Labor Time (276.4 ft ² area)	10.23 hours	30.68 hours	CLT requires ~67% less labor time due to simplified panel installation.
Electricity Use (Tally A5 Input)	15.48 kWh	46.16 kWh	Joist systems consume 3× more electricity during on-site construction.
Construction Emissions (A5)	77.79 kg CO ₂ eq	67.43 kg CO ₂ eq	Slightly higher for CLT due to grid energy mix, despite shorter labor time.
Material Waste	Low (factory-cut, minimal on-site waste)	High (on-site cutting, multiple components)	CLT reduces site waste significantly.
Overall Environmental Impact	Lower embodied carbon; efficient, low-waste assembly	Higher emissions; more components and site labor needed	CLT offers greater carbon and material efficiency in modular construction.

5.0 Conclusion

This study confirms that cross-laminated timber (CLT) systems offer substantial environmental advantages over conventional joist-based systems in modular construction. CLT panels demonstrated 42% lower embodied carbon (GWP), reduced labor time by 67%, and consumed 66% less construction-phase electricity. Despite slightly higher acidification and smog formation impacts during manufacturing, CLT’s benefits, such as reduced material waste, simplified installation, and factory precision, offset these drawbacks across the life cycle.

CLT enables more efficient, low-carbon construction suitable for affordable, volumetric modular housing. To maximize these benefits, future efforts should prioritize local sourcing, transport optimization, and broader life cycle modeling, including end-of-life and reuse scenarios.

5.1 Recommendations for Practice and Policy

The findings of this research show that CLT-based modular construction significantly reduces embodied carbon through carbon sequestration, prefabrication, and material efficiencies. The study presents direct implications for stakeholders involved in affordable housing delivery, including:

- Policymakers should form policies that incentivize the use of low-carbon materials in housing developments. This could include tax credits, expedited permitting processes, or carbon offset credits for developers that use biogenic materials like CLT.
- Architects and designers should prioritize mass timber in the early design stages to maximize carbon reductions while benefiting from the structural and aesthetic versatility of CLT.
- Developers using volumetric mass timber will benefit from reduced construction time and labor costs. As shown in Table 2, installation time and CO₂ emissions were greatly reduced compared to conventional joist systems, enabling quicker project turnover and reduced on-site emissions.

5.2 Research Gaps and Future Work

This study focused primarily on floor and ceiling systems under limited transportation and installation conditions. Future research should explore whole-building comparisons, detailed transport logistics (weight-volume tradeoffs), end-of-life pathways, and fire resistance performance of mass timber in modular settings.

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