Life Cycle Analysis of Mass-Timber Beams

Life Cycle Analysis, Civil Systems Engineering

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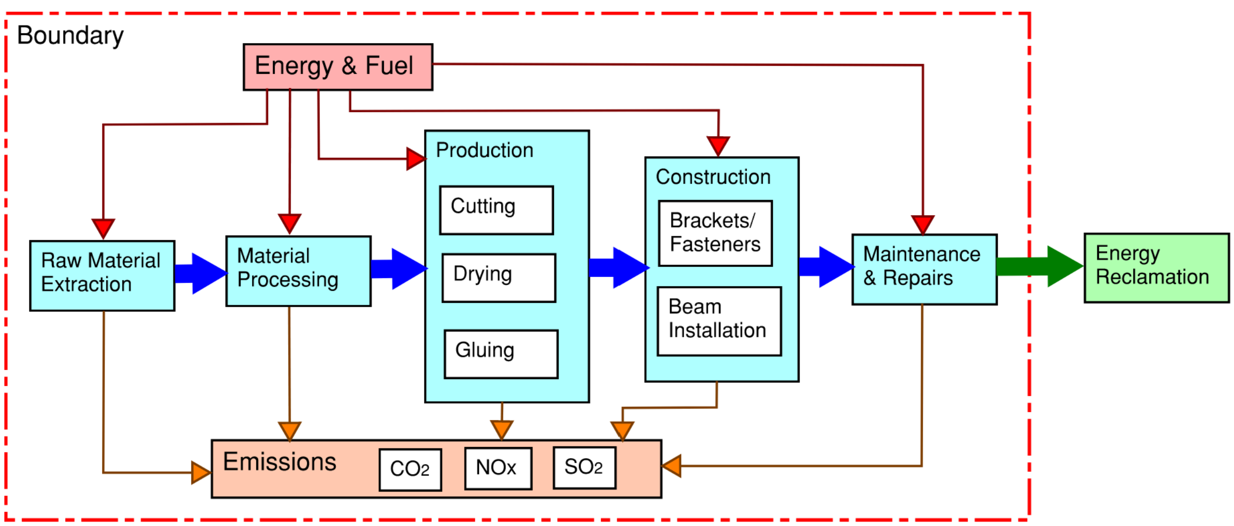
Introduction & Methods

As temperatures around the globe rise, and in-depth studies reveal how much standard building materials contribute to that warming effect, engineers and designers must look more into alternative options. Newer manufacturing techniques allow us to form innovative materials such as structural lumber - but how much do these alternatives contribute to emissions?

In this Life Cycle Analysis (LCA) study, we explore three different types of mass-timber beams commonly used in residential or light commercial buildings. The energy consumed and emissions produced in the lifetime of each beam type are assessed and ranked by importance, resulting in a comparative analysis of their associated carbon footprints.

Goal & Scope

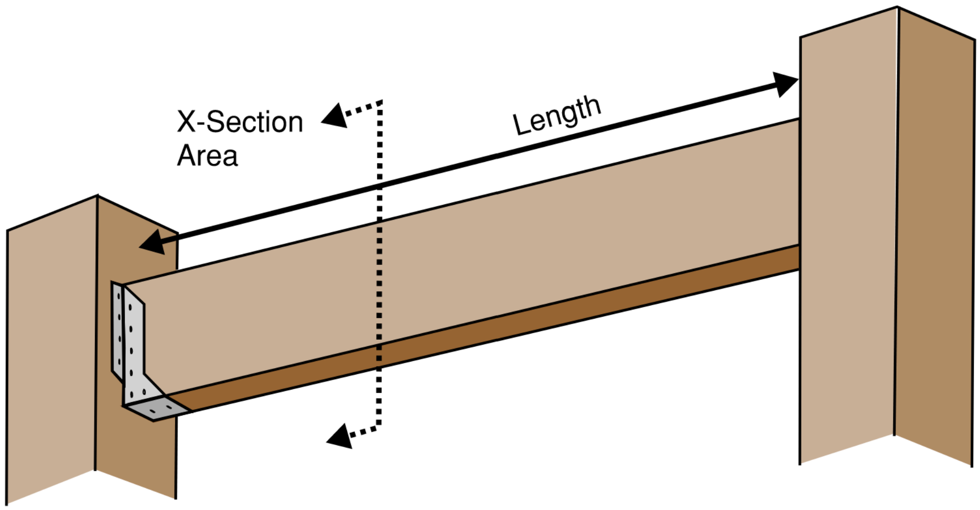
This analysis is based on mass-timber beams found in timber-framed residential buildings, with the goal of comparing the carbon footprints of Laminated Veneer Lumber (LVL), Glue Laminated Timber (GLT), and Cross Laminated Timber (CLT). The boundaries of the system analysis are depicted below:



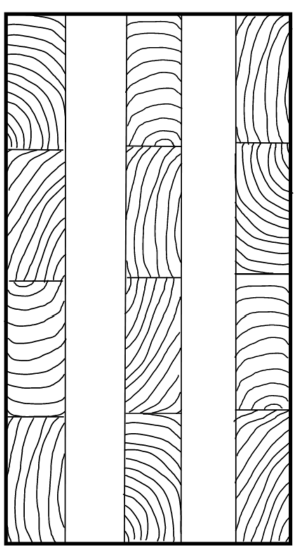
The energy required for wood harvesting, initial processing, beam production, construction, and beam maintenance will be quantified, as well as the emissions from those lifecycle stages. Due to time constraints and limited data sources, the potential energy reclamation often associated with wood products will be excluded. In future studies, it is recommended that burning wood waste as an alternative fuel, carbon capture post-construction, and other recovery methods be included for a more holistic analysis. As it stands, we will focus only on non-renewable energy and emissions in this report.

Material Properties

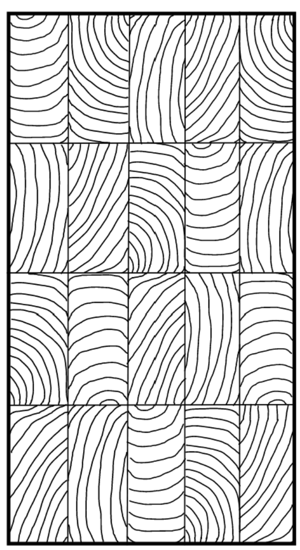
For a proper comparison, we must first define the beams and their materials; the mass-timber beams will be characterized by their cross-sectional area and length, as shown in the sketch below:



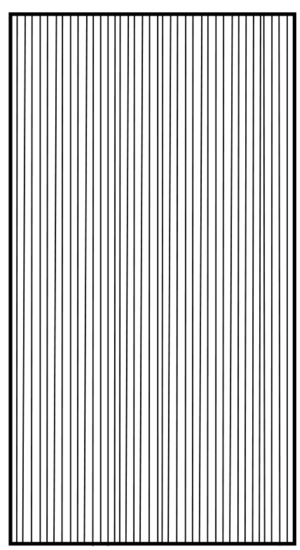
Each beam type has a different configuration of wood components, resulting in various types of cross sections. Cross-Laminated Timber (CLT) is composed of wood studs oriented so that the grain of each layer is perpendicular to that of the neighboring layers. By contrast, the wood grain of each Glue Laminated Timber (GLT) layer faces the same direction throughout the beam. The final beam type, Laminated Veneer Lumber, is composed of many layers of thin wood veneers, typically about 3-5mm thick.



CLT Beam
Cross-Section



GLT Beam
Cross-Section



LVL Beam
Cross-Section

All three beam types are pressed tightly together with high-strength glue, typically Phenol-formaldehyde (PF), until all components perform as one composite beam. The resulting materials are rigorously tested and graded before being deemed usable. They are then transported to the project site, and attached to posts using fasteners such as brackets or plates. For our study, we will analyze the following three design options:

Design Option	Beam Material	Fastener Type
Option 1	LVL Solid Beam	Timber Bracket
Option 2	GLT Solid Beam	Plate Fastener
Option 3	CLT Solid Beam	Timber Bracket

We define the materials as shown in the table below. All beam types are assumed to be hardwood, fully-edge glued, and placed under typical loading patterns for a residential building. The functional unit is a 1 meter long beam span. Assume for the GLT and CLT beams that each layer is ⅕ th of the cross-section width (Balasbaneh, A. Sher, W.), and for the LVL beam that veneers are 3mm layered lengthwise (Lu, H.). The fastener cross sections are calculated as if folded flat, with two plates on either side and one set of fasteners for each end of the beams. Bolts and screw weights are included.

Element	# Layers	Cross Sectional Area (m^2)	Density (kg/m^3)	Weight (kg) for 1.0 m FU
LVL Solid Beam	47	140x240 (mm) = 0.034	787	26.44
GLT Solid Beam	5	135x406 (mm) = 0.055	480	26.44
CLT Solid Beam	5	135x406 (mm) = 0.055	480	26.44
Timber Bracket	-	620x160 (mm) = 0.099 (thickness 8mm)	7800	12
Plate Fastener	-	406x230 (mm) = 0.093 (thickness 16mm)	7800	47

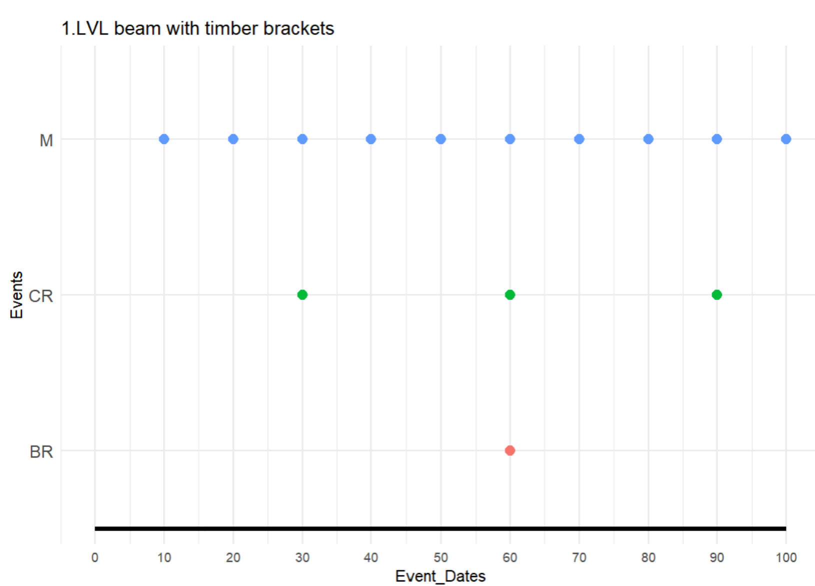
Timeline & Interventions

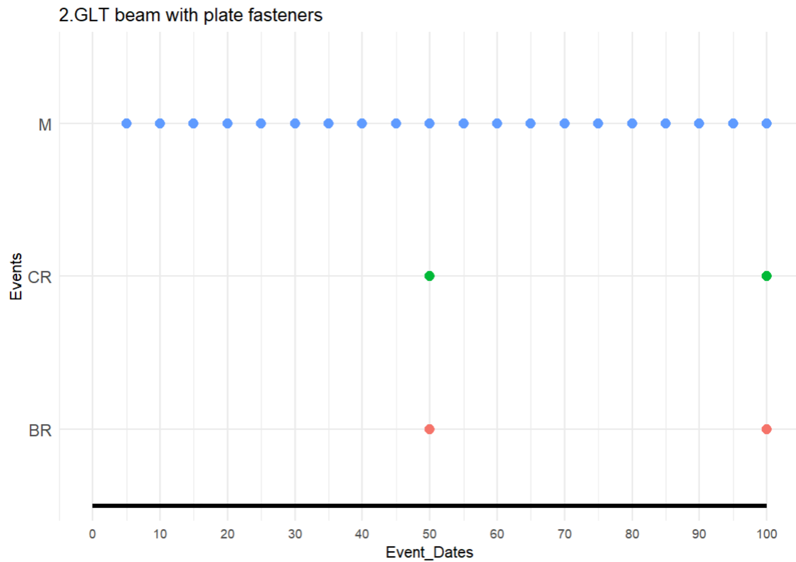
The lifespan of a typical timber-framed residential building is around 100 years, as confirmed in multiple sources and the Fault-Tree project associated with this report. During this lifetime, there are several maintenance and repair events that a beam system may need to undergo. We assume that GLT and CLT beams are similar enough to require the same frequency of beam-specific maintenance, and that the thicker bolts used in the plate fasteners are more durable than the threaded screws in the timber brackets. The interventions are summarized in the following table:

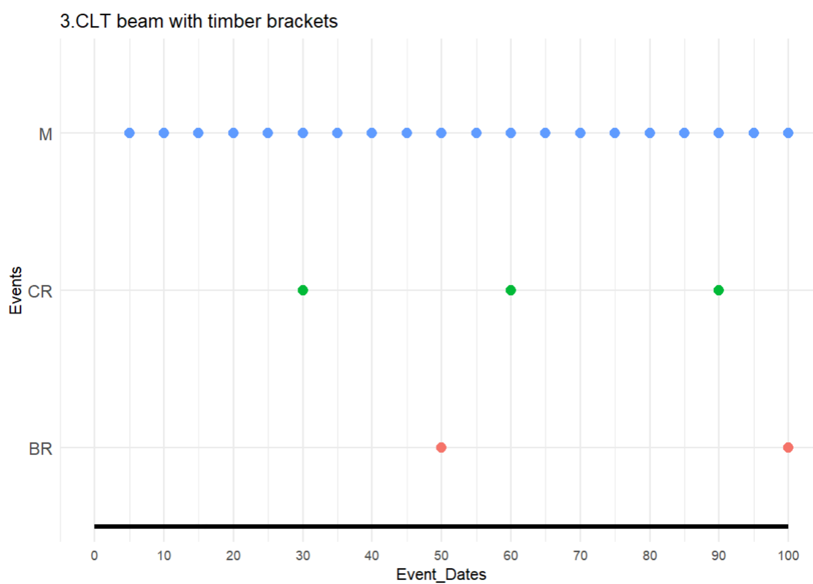
Design Option	Event	Frequency	Total Lifespan
1. LVL Beam with Timber Brackets	M	10	100
1. LVL Beam with Timber Brackets	CR	30	100
1. LVL Beam with Timber Brackets	BR	60	100
2. GLT Beam with Plate Fasteners	M	5	100
2. GLT Beam with Plate Fasteners	CR	50	100
2. GLT Beam with Plate Fasteners	BR	50	100
3. CLT Beam with Timber Brackets	M	5	100
3. CLT Beam with Timber Brackets	CR	30	100
3. CLT Beam with Timber Brackets	BR	50	100

M = beam & connector maintenance
CR = connection partial replacement
BR = beam partial replacement

We can plot these interventions on timelines specific to each design option, so that maintenance or repairs can be planned accordingly. Major interventions can be combined, to minimize mobilization and time costs.







Life Cycle Inventory

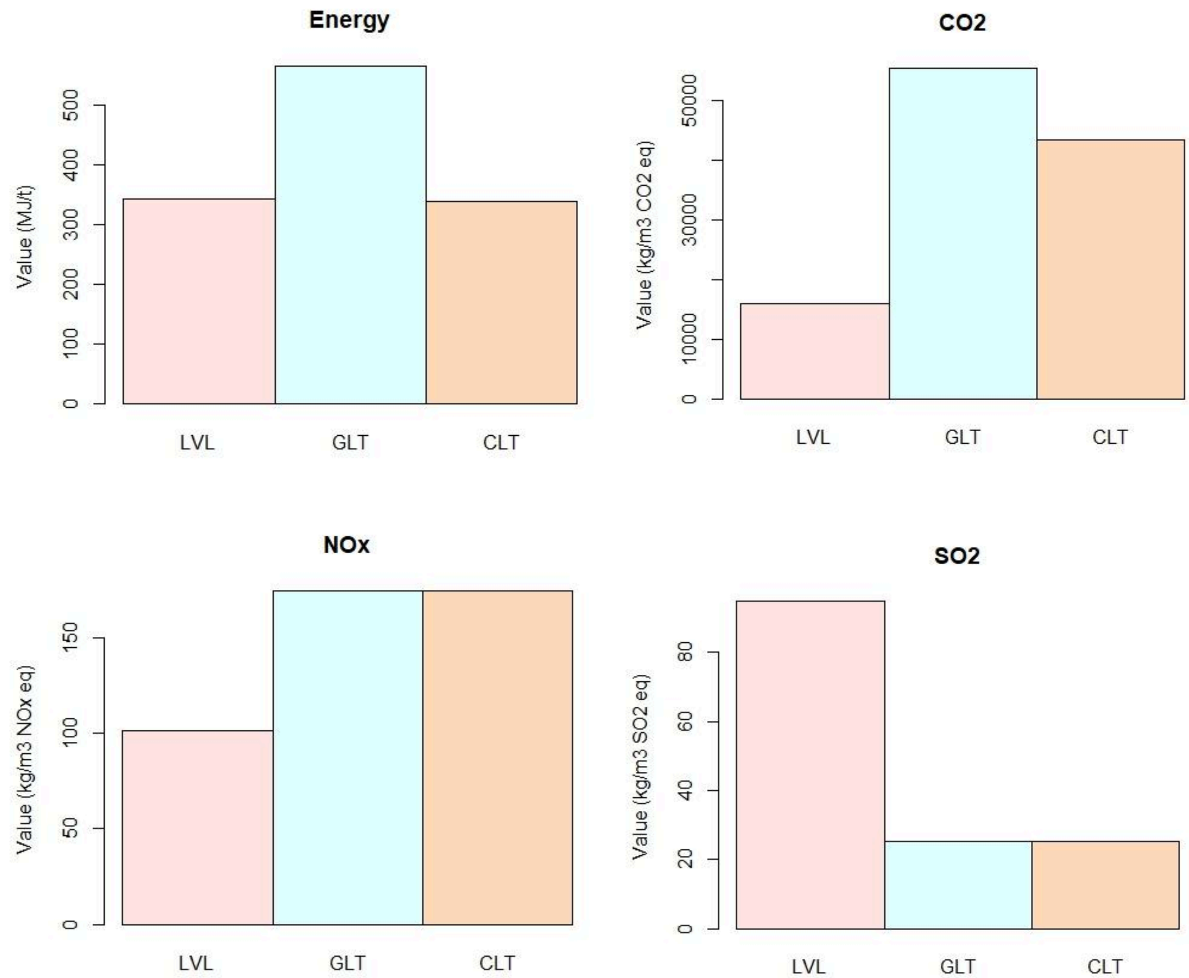
At the end of the beam's lifetime, we can total the amount of energy and emissions used in the process for each material component. For this report, we will analyze the embodied energy, the amount of CO_2, NO_x and SO_2 emissions. The wood studs used for both GLT and CLT were deemed comparable (Demirovic, E.), although from one study we find that the overall production of CLT studs use 40% less Energy than GLT, and 22% less CO_2 than GLT (Balasbaneh, A. Sher, W.). The LVL veneers are assumed to be 3mm (Puettmann, M.).

Material	Scope	Quantities	Energy (MJ/t)	CO2 (kg/m3)	NOX (kg/m3)	SO2 (kg/m3)
Wood Veneers	LVL	787 kg	2132	100	0.63	0.59
Glue/Resin	LVL	5 kg	183	16	0.01	3.24
Steel	timber. brackets	1	2430	225	0.71	1.85
Wood Studs	GLT	480 kg	1786	175	0.55	0.08
Glue/Resin	GLT	5 kg	183	16	0.01	3.24
Steel	plate. fasteners	1	2430	225	0.71	1.85
Wood Studs	CLT	480 kg	1072	137	0.55	0.08
Glue/Resin	CLT	5 kg	183	16	0.01	3.24

Although the Phenol-formaldehyde (PF) glue is shown in this table, it was excluded from the LCA seeing as it is used in all three products in near-equal amounts (Perederic, O.) and as there is little data relating to its individual emissions. For future studies, it may be worthwhile researching different types of high-strength adhesives to be included for comparison.

Life Cycle Analysis

We can now sum the energy and emissions consumed in the processing, machining, construction and maintenance for each beam design option. We use a beam length of 6 meters, for a representative residential housing span. The volume of materials is calculated for all beam and fastener combinations, and a matrix is created of quantities and intervention values for all three options. The energy and emissions are then calculated based on the values in the previous table, and visually represented in barcharts on the following page.



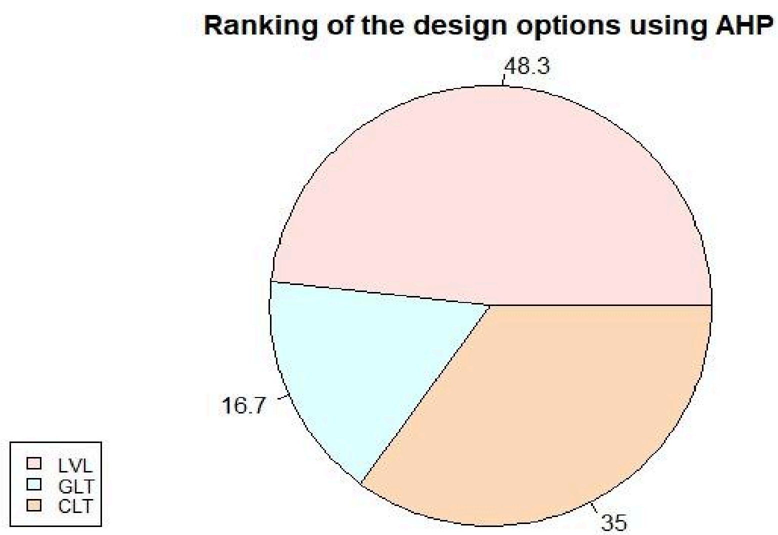
From the graphs above, it is obvious that GLT consumes more energy and CO_2 than the other beam options, and that the LVL design option performs the best in most categories besides SO_2 emissions. That being said, it can be difficult to visually compare them in a way that allows a designer to make a confident choice in beam selection. It is therefore imperative that we conduct a multi-criteria decision analysis to select the best design option.

Analytic Hierarchy Process Selection

The Analytic Hierarchy Process (AHP) allows us to sift through complex information, like the values presented in the bar charts above, in order to select the best alternative for our goal. In this criteria analysis, different weights were assigned to the design options - both within the energy and emission categories, and to those larger four categories themselves.

In general, the lowest value column was favored highly, and equally valued columns were set to equal importance for simplicity. The CO_2 category was given the highest priority, as our main goal was to analyze the carbon footprint of each beam. Although an expanded system boundary including the carbon capture that wood performs even after component assembly would lower the values displayed in the bar charts, we want to give CO_2 more influence as one of the main contributors to global warming.

Energy was given the next highest priority. Similar to CO_2 emissions, including end-of-life would allow for incorporating energy recovery from burning wood waste and other such methods. However, the values used in this project were from non-renewable sources so we therefore want to minimize the amount of these sources used as much as possible. The final two emissions were given similar importance levels, with SO_2 slightly lower as a larger portion of the contributions may have come from the steel. The overall results are displayed in the pie chart below.



The AHP analysis confirms our suspicions from the bar charts, that the LVL design option is the favorable one. That being said, it must be noted that LVL had dramatically higher SO_2 emissions than the other three options. In our ranking system, SO_2 was the least important emission so this outcome makes sense, but this proves that no single material can ever be perfect.

In other analyses, one of the other beam options may prove the better option. For example, if this report had factored strength into the selection criteria, then we may have found that GLT would perform the best despite its higher emission and energy levels (Architecture I.). Additionally, a study into reclamation and recycling might suggest that other options are superior.

To conclude, while in this study Laminated Veneer Lumber was chosen as the best design option due to its lower carbon footprint, another type of mass-timber beam might perform better under different goals. Analyses must therefore be extremely focused and clear when collecting data and reporting results, especially when using multi-criteria decision making such as the AHP method.

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