Platte Fifteen Life Cycle Assessment

Platte Fifteen | Oz Architecture.
Photo courtesy: JC Buck

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ABOUT THINK WOOD

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Executive Summary

Mass timber structural systems are relatively new to the North American construction market, but their use is growing rapidly as new manufacturers and supply chains begin operations, creating a cycle of familiarity and cost competitiveness with other structural systems. Owners, developers, architects, engineers, and builders are led to consider mass timber structural systems for a variety of reasons, among them aesthetic, biophilic design, speed of construction, renewable resource use, and carbon sequestration. The importance of reducing the embodied carbon impact of building construction gives a sense of urgency to the last category, but adoption ultimately depends on competitive pricing for mass timber which can be hindered by a lack of familiarity with the material and its construction management, at least for initial projects.

The building industry has made improvements to operational energy consumption over the last 20 years. Attention is now pivoting to embodied carbon, which is the emissions associated with physical materials through their extraction, production, construction, and disposal. This carbon impact is quantified using Life Cycle Assessment (LCA), with the primary measure expressed as Global Warming Potential (GWP) in units of kg of CO_2 equivalent. The 39% of global emissions attributed to the building industry is currently made up of 28% operational emissions and 11% embodied emissions, and the focus on reductions to operational energy are making headway while embodied carbon emissions are just beginning to garner mainstream attention (Architecture 2030, 2020). Unlike operational carbon whose impacts can fluctuate, and continue over a building's useful life, embodied carbon impacts are immediate and permanent. When considering anticipated new construction between 2020 to 2050 and the target reductions of operational carbon, embodied carbon will account for roughly half of carbon emissions, equivalent to operational carbon (Architecture 2030, 2020).

Because mass timber sequesters carbon, it is an increasingly important component in a broad, multi-faceted strategy to reduce embodied carbon that will ultimately require consideration of all building materials. Several studies have used LCAs to quantify the reduction in embodied carbon that can be achieved with mass timber (Jensen, 2020) (Simonen, 2019) (Gu & Bergman, 2018); unfortunately, there remains the challenge that mass timber has a perceived cost premium over conventional structural materials. The purpose of this study is to combine a comparative structural life cycle assessment with realistic cost estimates on a constructed project to understand the economic impact of sustainable material choices.

This study compares the embodied carbon, construction costs, and speed of construction of three functionally equivalent buildings in mass timber, steel, and concrete, all based on a reference building which is an actual mass timber office building in Denver, Colorado. The constructed reference building, Platte Fifteen (WoodWorks Wood Products Council, 2020), was the largest mass timber building in Denver, Colorado at the time of its construction in 2019, with an above grade floor area of 150,000 ft² (14,000 m²), and reaching a height of 70-feet (21.4-meters) Constructed by general contractor Adolfson and Peterson (A&P) for developer Crescent Real Estate LLC. The building is four levels of Type IIIB construction over Type IA concrete podium with two levels of below-grade parking. The design team included architect OZ Architecture and structural engineer KL&A Engineers and Builders.

The alternate steel and concrete structural systems evaluated in this study were designed by KL&A using the same grid (typically 30 ft x 30 ft) and design criteria as the original building.[1] The same lateral load resisting systems and foundation systems were used for all three buildings, and they were redesigned for each in response to minor changes in building weight. The cradle-to-grave structural LCAs of the structural systems, plus a cradle-to-grave life cycle assessment of the vertical enclosure, ceiling finishes, and roof enclosure were performed by KL&A, utilizing Tally® software as described in the section "LCA Methodology and Material Assumptions." Construction costs and construction durations for all three systems were provided by the original contractor, A&P, as described in the section "Comparative Cost Study."

The Platte Fifteen building was chosen for study primarily because, as a completely designed and constructed mass timber building, the accuracy of cost and material quantity information for mass timber was excellent. However, the building design included two levels of below grade structure on a site with a high-water table, and one level of concrete above grade, so material quantities and associated embodied carbon quantities were dominated by concrete. This aspect has important implications regarding the impact of concrete on embodied carbon,

but it also obscured the relative impact of comparisons between the three framing systems. To account for this, results are presented both for the entire structure and for the portion of the structure above the concrete podium.[2] In this way, the results can be considered in the context of the whole building responding to this site, and also as a smaller building with no below-grade structure or podium.

The key results of the study include the following:

- Considering only the framing structure above the podium, the mass timber GWP was 34.4 $kgCO_2eq/m^2$, a 70-76% reduction compared to steel and concrete, at 113.5 and 141.8, respectively. This is largely due to the natural ability of mass timber to sequester carbon (Figure 1).

- While the mass timber contributes 45% of the mass of the framing structure above the podium, it contributes less than 1% of the GWP.

- Considering the entire structure and enclosure the mass timber choice was less impactful, resulting in only a 10-11% reduction in GWP. This result reveals how significant the impact of concrete on embodied carbon totals can be.

- As EPDs (Environmental Product Declaration) and industry LCIA (Life Cycle Inventory Assessment) data become more readily available within LCA tools and the standardization of materials, product, and building LCAs evolve, building LCA results and comparative studies will become more potent and accessible. In the meantime, relative impacts can inform system and product selection, and significant "hot spots" within the assessments can be identified.

- Comparing the time of construction, the mass timber structure was expected to be erected 2 months faster than the steel structure and 3.5 months faster than the concrete structure. This time savings benefits both the cost and the carbon impact of mass timber system.

- Considering only the material costs of structure and vertical enclosure, the steel structure was the least expensive, with concrete showing a premium of 3.3%, and mass timber a premium of 8.4%.

- Considering the effect of time savings for mass timber on general conditions (labor), general requirements (equipment, etc.), and crane time, the premium for concrete over steel increased to 3.9%, and the premium for mass timber decreased to 4.9%.

- For Platte Fifteen, the structure cost relative to the total building cost was high (40%), due to the amount of sub-grade parking structure and foundations. Even at this high percentage, the 4.9% mass timber premium on structure translates to less than 2% of the building cost.

Savings to the building owner associated with the time-value of money resulting from earlier completion of the mass timber structure, or the favorable lease rates associated with the exposed wood aesthetic were not included in this analysis, although they had a positive impact on the economic success of the built structure. The building was 85% leased within one month of completion, and lease rates were above any other low to mid-rise office building in the Denver central business district. Similarly, taller structures (e.g. 9-story Type IV-C buildings) were not included in this study, but it is not unreasonable to speculate that the cost comparison would have been even more favorable to taller mass timber structures due to the accumulation of construction speed efficiencies.

While it is not commonplace at the time of this writing, it is expected that soon there will be systems in place to monetize carbon savings directly. It may be that the small premium for mass timber in this building could be offset in whole or in part by carbon credits.

In conclusion, this study has shown that, for one representative office building under realistic conditions, the design choice of mass timber can bring consequential savings in embodied carbon for little to no building cost premium (Figure 2).

[1]*A minor change in the concrete grid was adopted to represent better common practice. This change worked to the advantage of the concrete building in terms of both cost and GWP.*

[2]*All results presented "above the podium slab" include only the column, framing, and floor plate assembly of each framing system.*

Total GWP/M² Above Podium Slab Per Building System

GWP/M² (kgCO$_2$eq/m²)

Materials
- Wood
- Metals
- Concrete

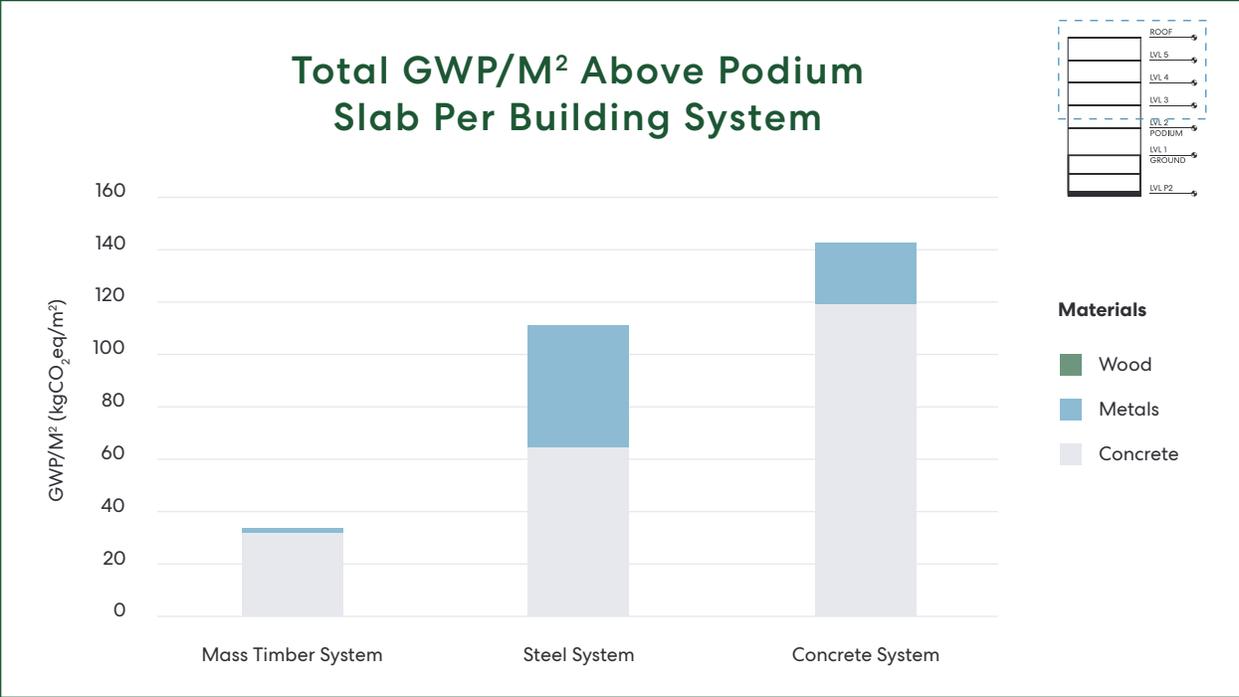Mass Timber System Steel System Concrete System

Figure 1. Total GWP per square meter above the podium slab for three building systems, showing contributions in each from three material categories. Mass timber's GWP contribution of 0.33 per m2 is so small, it does not appear in the chart.
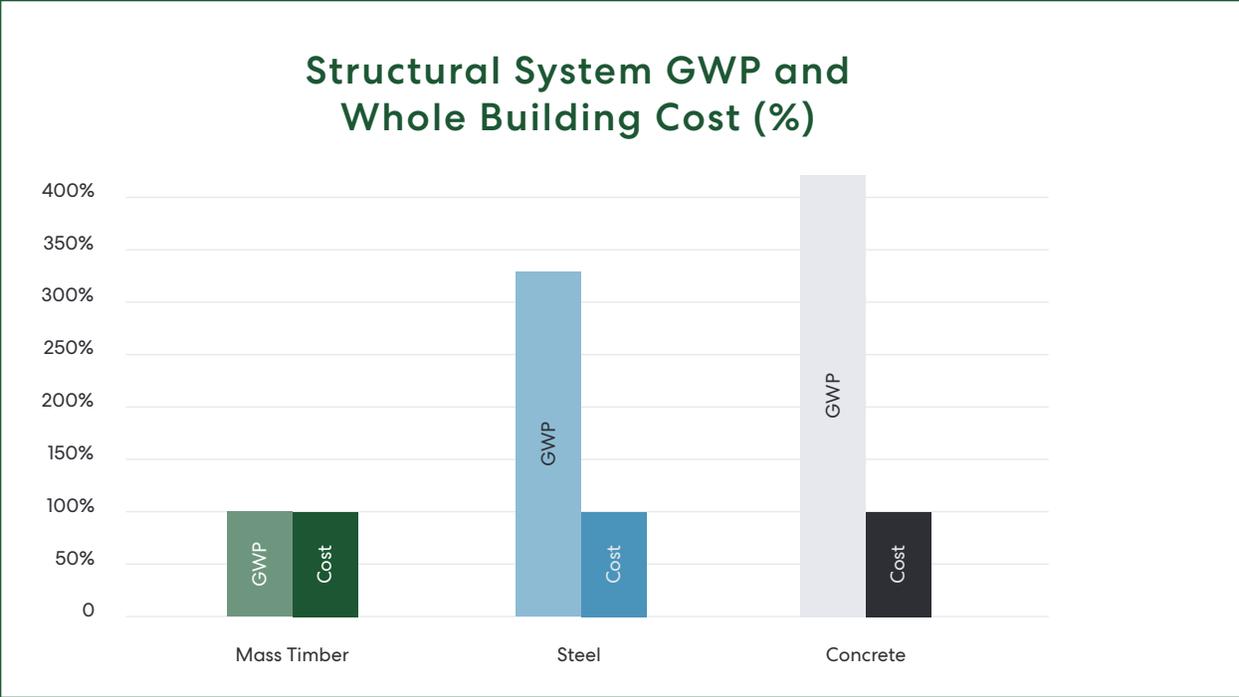

Structural System GWP and Whole Building Cost (%)

Mass Timber Steel Concrete

Figure 2. Comparison of the structural system GWP (above the level two podium slab) and the whole building cost of the three systems.

Introduction

The purpose of this study is to combine life cycle assessment with cost estimates on a completed building project to understand better what the embodied carbon and economic implications are of choosing mass timber, steel, or concrete structural systems. The study is based on an existing reference building – the mass timber office in Denver known as Platte Fifteen – as it compares to design alternates in steel and concrete. Comparisons between the three systems are made in terms of embodied carbon, speed of construction, and construction cost.

This report starts with an introduction to embodied carbon and its measurement followed by a description of the reference and design alternate buildings. The details of the LCA methodology are documented next, and finally the results of the LCA and cost comparative analyses are presented.

Embodied Carbon and Its Measurement

The core work in this study is the quantification and comparison of embodied carbon in three functionally equivalent buildings. Building embodied carbon is measured using Life Cycle Assessments (LCA), which are founded on Life Cycle Inventory (LCI), Life Cycle Inventory Assessment (LCIA), and Environmental Product Declarations (EPD). LCAs are used to quantify the associated emissions and various environmental impact categories of a building, system, assembly, product, or material and encompass specific stages, such as cradle-to-gate or cradle-to-grave. EPDs are externally verified summary reports of LCA results of a specific product or product group (industry average). LCI data is the collection of accounting of a product's energy and material input and output which is then converted into environmental impacts, resulting in LCIA data. LCAs, LCIA, and EPDs are estimates of environmental impact and greenhouse gas (GHG) emissions based on current available science and best practice.

The standard Life Cycle Stages are represented in Figure 3. The scope for this comparative building LCA is cradle-to-grave, including Module D: Reuse, Recycle, and Energy Recovery. The stages excluded from the assessment are construction impacts (Stage A5), operational energy impacts (Stage B6), use (Stage B1), and demolition (Stage C1). The life for all materials are assumed to be the same as the assumed building life, which is 60 years; therefore, Stage B2-B5: maintenance, repair, replacement, and refurbishment is included within the scope, but has no impact in this study.

Various environmental impact categories are considered in LCAs, including Global Warming Potential (kg CO_2eq), Acidification Potential (kg SO_2eq), Eutrophication Potential (kg Neq), Ozone Depletion Potential (CFC-11eq), Smog Formation Potential (kg O_3eq), and Energy Demand (MJ). This study focuses on Global Warming Potential (GWP) because it is the impact factor that represents all GHG emissions that occur during the life cycle of the building components which create the conditions for global temperature rise.

Quantifying embodied carbon is a relatively new approach used to measure the GHG emissions associated with the construction of buildings versus building operations; it was previously identified as embodied energy.

Life Cycle Stages & Study Scope

Product			Constr-uction		Use							End-of-Life				Module D		
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D1	D2	D3
Raw material supply	Transport	Manufacturing	Transport	Construction\Installation	Use	Maintenance	Repair	Replacement	Refurbishment	Operational Energy Use	Operational Water Use	Deconstruction	Transport	Waste Processing	Disposal	Reuse	Recycling	Energy Recovery
✓	✓	✓	✓			✓	✓	✓	✓				✓	✓	✓	✓	✓	✓

Figure 3. Life Cycle Stages[3] as defined by EN 15978. Processes included in Tally modeling scope are shown in bold. Italics indicate optional processes.

[3]See Appendix for Tally® Life Cycle Stage Methodology.

Due to the complex nature of the analysis, the paucity of manufacturer product specific EPDs in building LCA tools, and the need for more comparable data across product types, some uncertainty in building component data is acknowledged. While the phrase "uncertainty" may be unsettling, the primary objective in preparing LCAs is to help direct immediate action to reduce emissions associated with buildings, with full knowledge that the current methodology is evolving. The data and methodology will progress through collective analyses, and as more aspects of material impacts are explored, and nuances further understood. This study endeavors to be transparent in methodology and assumptions, with the intent to identify possible pathways for immediate embodied carbon reductions.

Buildings and Scope

This section describes the scope of the study, first in relation to the buildings studied, and then in terms of the LCA study itself.

mass timber, steel, and hybrid CLT and steel framing. All options were studied and compared in a formal "Choosing by Advantages" (CBA) process to select the most effective system with respect to aesthetics, construction speed, floor-to-floor height, and material cost (WoodWorks Wood Products Council, 2020).

The design and construction team were led by Crescent Real Estate LLC, with Adolfson and Peterson Construction (A&P) as the general contractor, OZ Architecture as architect, and KL&A Engineers and Builders as structural engineer. The alternate steel and concrete systems evaluated in this study were designed by KL&A and priced by A&P. The three building systems investigated in this study have the same footprint, the same 30 x 30-foot typical grid, and are functionally equivalent.[4] All three structural framing types utilize the same (original) construction systems from level L2 to the foundation, with designs modified for the different loads imposed from levels L3 to the roof.
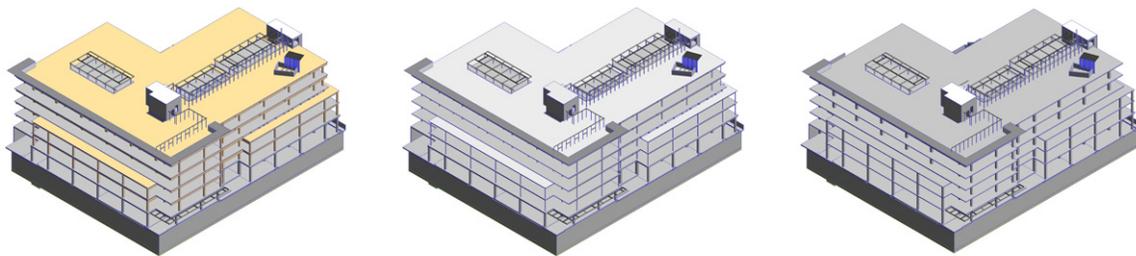

Figure 4. Isometric representation of the three structural framing systems: mass timber, steel, and concrete.

Building Description

This study compares three commercial building structural framing systems: mass timber, steel, and concrete (Figure 4). The reference building is a constructed office building with below-grade parking known as Platte Fifteen. At the time of construction in 2019, Platte Fifteen was the largest mass timber building in Denver, standing at 70-feet (21.4-meters) with five levels above grade. It is Type IIIB over Type IA construction conforming with the 2015 IBC, totaling approximately 230,000 square feet (21,000 m²), 150,000 square feet (14,000 m²) of which are above grade. The grid and glulam framing were optimized early in the design process in collaboration with the architect, contractor, and timber fabricator. For the original design, three different structural material systems were considered during the schematic design phase, including

The designs for the three framing systems from level L2 and below, including the foundations, are essentially the same, with slight modifications due to increased framing weights where required. The below grade construction reaches 7-feet below the water table, resulting in a waterproofed 32-inch mildly reinforced cast-in-place concrete mat slab and 10-inch-thick cast-in-place concrete foundation walls. The main level and first level below grade are comprised of 12-inch thick mildly reinforced cast-in-place concrete slabs and concrete columns. Considered in this light and as a whole, the building is essentially a large concrete structure, with only four stories above the podium varying for this study.

The following are the three gravity systems above the level L2 podium slab podium slab for comparison:

[4]A minor change in the concrete grid was adopted to represent better common practice. This change worked to the advantage of the concrete building in terms of both cost and GWP.

Mass Timber System:
Floors are 3-ply CLT floor panels (3 ½-inch thickness) with 3-inch concrete topping slabs and the roof is 3-ply CLT panel. Beams and columns are all glulam supported at level L2 on a 16-inch post-tensioned concrete podium slab. Levels L1 and P1 are cast-in-place concrete slabs with mild reinforcing, supported on a concrete mat foundation.

ROOF
LVL 5
LVL 4
LVL 3
LVL 2
PODIUM
LVL 1
GROUND
LVL P2

Figure 5. Schematic section of the referenced building.

Steel System:
Floors are concrete on composite steel deck (6-inch total thickness) supported on composite steel beams and girders. Roofs are 3-inch steel roof deck on non-composite steel beams and girders. Columns are steel wide flange and HSS tube sections supported on the same concrete systems at levels L2 and below as the "Mass Timber System."

Concrete System:
Floors and roof are 8-inch post-tensioned concrete slabs, supported on cast-in-place concrete columns. The level L2 slab is 8-inch post-tensioned concrete, supported on the same concrete systems at levels L1 and below as the "Mass Timber System."

Denver is a region of low seismicity and moderate winds, with a design ultimate wind speed of 115 mph. Seismic loads governed the lateral design for all three buildings. The following describes the three lateral systems for comparison:

Mass Timber and Steel:
(2) 10-inch cast in place concrete cores and single-bay steel rod braced frame at the northeast elevation.

Concrete:
(2) 12-inch cast in place concrete cores and a single bay concrete shear wall at the northeast elevation.

The building vertical enclosure is the same for all three cases, glass, brick, and metal panel with a fire resistance rating of 1-hour at the superstructure. The constructed
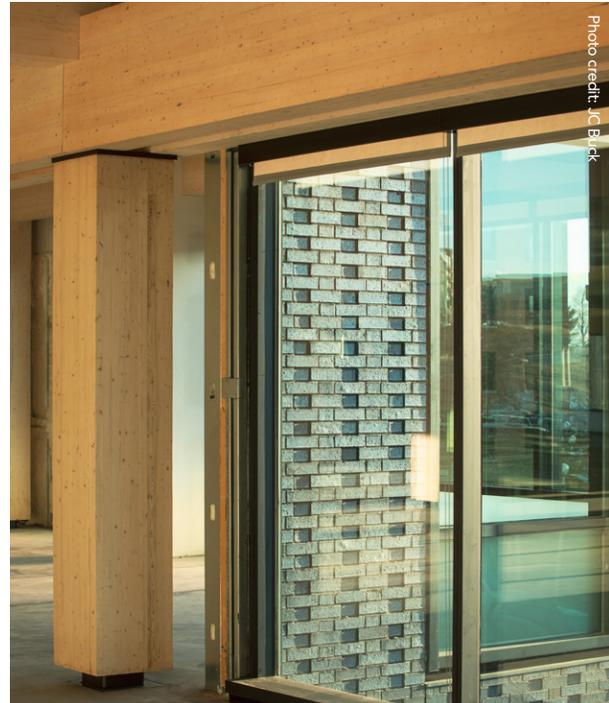
ceiling finish in the reference mass timber system was minimal, consisting of gypsum board, suspended metal framing, and insulation separating parking from retail and office space, no ceiling finishes in the remaining parking areas, and no finishes at the mass timber levels, leaving the CLT floor, glulam columns and beams exposed. The steel and concrete buildings did not include additional ceiling finishes at the above grade levels at the alternate framing systems. Although in practice the steel and concrete floor systems would likely have additional ceiling coverings, speculation of aesthetic preference was avoided, to not artificially inflate their GWP and costs. The typical roof enclosure is a TPO assembly, comprised of TPO roof membrane and polystyrene insulation.

The mass timber and steel systems are very similar in most respects except material choices. There are more structural differences in the concrete system due to the increased weight and associated increased seismic mass, and the lower floor-to-floor height. For the concrete system, the core wall thickness increased from 10-inches to 12-inches because of increased lateral loads. In the mass timber and steel systems, the level 2 podium slab transfers loads from columns that are slightly offset from the columns below in order to maintain regularity in the timber framing; in the concrete system, the level L2 slab is thinner because it does not transfer column loads.

In designing the alternate concrete system, it was decided that, because concrete slabs can economically accommodate variations on grid spacing of a couple

Photo credit: JC Buck

feet, that is how an alternate would be designed. Another attribute common to post-tensioned concrete structures is very efficient floor-to-floor height: there was a reduction of one foot per floor while maintaining the same clear height to structure, totaling an overall building height reduction of five feet. This was important to capture as part of the material quantities and comparative pricing exercise.

LCA Scope

The scope of this comparative LCA study includes substructure and superstructure elements (floors, roofs, beams, columns, walls, lateral systems, foundations, steel reinforcement), rooftop mechanical support and screen framing, canopy structural framing, and above-grade parking crash walls. The building vertical enclosure, ceiling finishes, and roof enclosure are included in this study but presented as a separate LCA to allow the reader to consider finishes at their discretion while considering aesthetic and fire ratings of the different structural systems. The vertical enclosure assessment includes the cold-formed steel framing with batt insulation, rigid insulation, vapor barrier, and architectural finish to the exterior and interior faces and the glazing system, including mullions, spandrels, punched opening steel, and brick support. The ceiling assessment considers the gypsum board, suspended metal framing, insulation, and wood veneer. The roof enclosure assessment considers the TPO roof assemblies: typically, TPO membrane and polystyrene insulation.

Exclusions from the LCA's are architectural finishes not listed above, such as floor and interior wall finishes, paints, stains, sealers, and site, civil, mechanical, electrical, and plumbing scope. Structural exclusions from the LCA scope are the structural connections of framing members and miscellaneous metals. This exclusion is most generous to steel, as it is estimated that connection weight is about 5% of main members. The mass timber system utilized screwed connections for nearly all girder and beam framing and the concrete system used traditional steel reinforcement dowelled connections.

Embodied Carbon and Its Measurement

LCA Methodology and Material Assumptions

This comparative cradle-to-grave LCA study was performed using Tally®, whose methodology conforms to LCA Standards ISO 14040-14044, ISO 21930:2017, ISO 21931:2010, EN 15804:2012, and EN 15978:2011. Tally® is a plug-in application for Autodesk Revit® software, allowing users to define EPD and LCI data for BIM elements, resulting in an LCA for the selected modeled elements. Tally® was developed by KT Innovations, an affiliate of KieranTimberlake, and uses Thinkstep's GaBi database for LCI information and modeling principles (KT Innovations, 2020).

The results of this study are limited by specific EPDs and LCI data within the Tally® database, as well as the software's Stage C and Stage D disposal, reuse, and recycling mix assumptions. It is standard for EPDs to report Stages A1-A3, cradle-to-gate. Tally® provides the data for the remaining stages based on industry averages within the database. The major structural materials of this study – mass timber, wide flange steel, steel deck, concrete, and steel reinforcing are all reported using industry baseline EPDs.[5] The best option for comparative global warming potential studies is to use the same methodology and data sources for each LCA. The LCAs performed for this study follow Tally®'s calculation methodology.[6] Significant LCA, material, and end-of-life assumptions are presented in this section.

Mass Timber System

The Mass Timber building LCA did not consider the acoustic mat, a component of the structural floor assembly: CLT panel, ¾-inch acoustic mat (sound insulation board), and concrete topping slab. Tally® does not currently have an appropriate acoustic mat option. The acoustic mat's impact was estimated to be less than ½% of total GWP contribution, calculated using a nylon carpet EPD within the Tally® database, modified by using the mass of the acoustic mat. The reader should acknowledge the potential emissions impact of fossil fuel based acoustic, waterproofing, and finish products as these can be significant. Vapor barrier and waterproofing materials of the vertical and roof enclosure were considered in the architectural elements' LCA of this study.

Stage A4, Transportation, was included in the assessments. The mass timber products (glulam and CLT) specifically considered the truck transport distance from the manufacturer and supplier of the constructed reference building, of 3,490 km (2,169 miles) from Chibougamau in Québec, Canada, to Denver, Colorado. All other products: concrete, steel, metals, architectural elements, assumed default distances from the LCI data by truck, based on industry averages. As illustrated in the Results section of this document (Figure 10), transportation impacts are less than 1% of total building GWP for the steel and concrete systems and less than 5% for the mass timber system, even when considering the Canadian supplier's distance from the project site.

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[5]*EPD and LCI dataset selections of this study are provided in the Appendix.*

[6]*Tally®'s calculation methodology and standards, end-of-life allocations, and LCI sources are provided in the Appendix.*

Mass Timber

Although the Canadian supplier does have EPDs for their glulam and CLT products, they are not currently available within Tally®. In place of this, the American Wood Council's North American Glue Laminated Timber EPD was selected for glulam members and "Proxied by Glulam" data was selected for CLT panels. The American Wood Council's North American Glue Laminated Timber EPD is based on averaged North American data and is adjusted by Tally® to consider the different densities of CLT versus glulam, to create the "Proxied by Glulam" data.

The effects of this representative CLT EPD selection on cradle-to-gate GWP was explored. In support of this study, ten available CLT EPDs (from Germany, Canada, Austria, Italy, Spain, and Oregon) were compared to determine the spread of reported impacts. The trimmed mean reported cradle-to-gate (A1-A3) impact is -677 $kgCO_2eq/m^3$ compared to -705 for the Proxy by Glulam data and -619 for Nordic CLT. Applying the 12% reduction of Nordic to Proxy by Glulam (-619/-705), the effect on the total mass timber system GWP above the podium slab is negligible, less than ½%.

Biogenic Carbon Cycle

Negative GWP values within LCAs and EPDs represent stored carbon or avoided impacts (renewable resource and material recycling). Substantial net negative impacts are typically only realized with plant-based products due to their natural ability to sequester carbon.

Trees, like all plants, have a carbon cycle as they continuously exchange carbon with the atmosphere through an uptake during photosynthesis and a release during decomposition or burning; this carbon cycle is known as the biogenic carbon cycle. The biogenic carbon cycle for mass timber products starts when the tree is harvested from the forest (Stage A1), at which time it contains approximately 50% of elemental carbon by mass (S.H. & R.A., 2003). The carbon content entering the system after harvest, known as sequestered carbon, is then held until the mass timber reaches its end-of-life in the building when it is demolished or deconstructed, and then either buried in a landfill, burned for energy, recycled, or reused (Stages C and D).

There are several approaches for considering the biogenic carbon cycle when performing LCAs: focusing on the product stage, cradle-to-gate (A1-A3) which assumes the wood material's net biogenic carbon emissions are zero (neutral) and is therefore conservative towards potential permanent carbon sequestration at end-of-life, an approach evaluating cradle-to-grave (A-D) which allows consideration of the uptake, release, and potential permanent sequestration of biogenic carbon throughout the life cycle of the product, and dynamic approaches which are based on temporal considerations including when to account for the regrowth of the trees used for the wood products (Hoxha, 2020). Tally®'s static approach considers cradle-to-grave stages, considering the wood volume's carbon content as it enters the assessment at Stage A1 (uptake) and the final disposition of the carbon content at Stages C and D.

The mass timber building in this case study has 701,845 kg of glulam beams and columns, and 502,556 kg of CLT panels. To illustrate sequestered carbon potential of the mass timber building, the carbon and carbon dioxide storage of the harvested trees within the CLT panels are isolated and calculated as follows:

Figure 6. Wood contains an estimated 50% of elemental carbon.

Data:

- Unit volume of CLT = 1 m³

- Dry density of wood used[7] = 490 kg/m³

- % of carbon as weight of wood = 50%

Calculations:

- Stored carbon per kg of CLT = 1 kg x 50% = 0.5 kgCeq/kg

- Stored carbon dioxide per kg of CLT = 0.5 kgCeq/kg x (44/12) = 1.83 $kgCO_2eq/kg$

- Total stored CO_2 per unit volume of CLT = 1.83 $kgCO_2eq/kg$ x 490 kg/m³ = 898 $kgCO_2eq/m^3$

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[7] The density of wood is based off the Proxied by Glulam data within Tally®.

[8] Tally®'s end-of-life allocations, source of construction and demolition treatment methods and rates, and LCI sources are provided in the Appendix.

As this CO_2 is stored in the CLT product to be used in the LCA, it is considered an uptake (sequestered) of CO_2 from the atmosphere, and is designated as a minus quantity, or -1.83 $kgCO_2eq/kg$.

- CO_2 storage within the CLT panels at A1 = (-1.83 $kgCO_2eq/kg$) x 502,556 kg = -921,353 $kgCO_2eq$

Isolating the GWP impact to transport the CLT panels, (Stage A4), and comparing to the stored carbon dioxide in the CLT at the start of Stage A1, is performed to provide context to the sequestration potential of mass timber. Transportation impacts are comparable to only 10.4% of the sequestered GWP at the start of Stage A1.

- GWP to transport the CLT 3,490 km (2,169 miles) = +95,764 $kgCO_2eq$

The life cycle Stages A-C, product creation, transport, and end-of-life, continue releasing CO_2eq, thereby reducing the amount of net sequestered CO_2eq.

Most LCA software tools have a similar approach to biogenic carbon until reaching Stages C and D. It is generally acknowledged that the disposition of the mass timber at Stage D is critical in determining an accurate value of the embodied carbon with an LCA. Tally® establishes a mix of Stage D pathways determined from common practices in North America of 17.5% recovered (recycled), 17.5% incinerated with energy recovery, and 65% landfilled (Dovetail Partners, 2014).[8] The recycled and incinerated scenarios have well-established methods to account for sequestration: recycled sequesters all the carbon in the product and credits it (uptake) as avoided burden and considers the energy required to process; incineration with energy recovery releases all the carbon with a credit (uptake) for non-renewable energy creation. For the landfill scenario, scientists have used bioreactor lab research to estimate the GHG gas emissions from long term decomposition, and the amount of wood that does not decompose; both are a function of landfill operating conditions. Findings on the amount of landfilled wood that does not decompose can range from 50-80% according to values given in various product EPDs (Pak, 2020).

The Tally® landfill model used for mass timber results in 32% of the wood remaining in the landfill without decomposition, meaning total permanently sequestered carbon within the LCA. It is important to note that small changes in the mix of Stage D pathways such as using the upper range of 80% of landfilled wood remaining without decomposition, and different assumptions regarding landfill management can have a substantial impact on the resulting net embodied carbon. As an example, the Athena Impact Estimator for Buildings LCA software landfill model results in 69.6% of the wood remaining in the landfill without decomposition (Pak, 2020).

The following example investigates the impact of changing the mix of Stage D pathways beyond the standard Tally® assumptions for the CLT panels. These calculations are based on Tally®'s biogenic carbon accounting and Stage D landfill apportioning method (Biogenic Carbon 101, 2018). The CLT EPD (Proxied by Glulam) was used and the Stage D pathway mixes were varied to determine the alternative differences. Case 1 is the baseline, using Tally®'s Stage D mix assumptions:

From this investigation, Case 2, 100% incineration has the lowest GWP release of the four cases, implying that this is the best Stage D pathway mix to minimize GWP. However, as Tally® considers recovery as recycling (which involves grinding into wood chips for use in other wood products) and does not include an option for direct reuse for Stage D, this conclusion is considered incomplete. If all the CLT product was reused in another building cycle, and the sum of the two building cycles was considered, the reuse in Stage D would reflect longer term carbon sequestration in the CLT product and become the best Stage D choice for minimizing GWP and maximizing sequestration. Direct reuse of CLT is feasible due to its panelized construction and screwed connections. As illustrated in Table 1, variations in the Stage D assumptions of mass timber and other wood products can significantly affect their net GWP impact. Advancement in landfill management and direct reuse of mass timber would result in a significant improvement in the permanent sequestration of carbon.

Stage D Biogenic Carbon Accounting

Case	Incineration	Landfill	Recovery (Recycling)	Stage D: Released (GWP/m³)
1	**17.5%**	**65.0%**	**17.5%**	661.1
2	**100.0%**	0.0%	0.0%	423.2
3	0.0%	**100.0%**	0.0%	655.9
4	0.0%	0.0%	**100.0%**	912.4

Table 1. Stage D Biogenic Carbon accounting comparison with varying end-of-life pathways.

Steel

The Bull Moose Tube EPD was selected for this study to represent all HSS tube sections and is considered a typical manufacturer. Fabrication, Stage A3, usually contributing 4-8% of the total GWP of this product, is excluded from the EPD (Ritchie, 2020). Currently, Tally® does not have an EPD (or LCI data) for ASTM grade A500 steel that considers Stage A3. HSS tube accounts for 1% of total GWP within the steel system of this study; therefore, total GWP is considered unaffected by the exclusion of the fabrication impacts. All other structural steel shapes include fabrication impacts and are analyzed based on industry wide EPDs and LCI data.

Concrete

Cement accounts for 5% of total global GHG emissions, which becomes an obvious target for embodied carbon reductions (Levi, Vass, Mandova, & Gouy, 2020). Concrete mix designs used, were comparable across the three building systems for selected LCI data. The 28-day strengths were selected according to the constructed Platte Fifteen Construction Documents. On the other hand, this analysis deviated from the original construction documents regarding the fly ash content, which was selected to be as optimistic as could reasonably be assumed in terms of reducing GWP by indirectly reducing cement content. In other words, for the purposes of the LCA, fly ash content was increased to a reasonable maximum while considering finishability and speed of construction. Concrete elements assigned 0-19% fly ash content were considered sensitive to finish requirements and sequencing of construction. Those assigned 30-39% were those for which it was acceptable to reach their specified strength beyond 28-days (see Table 2). The EPD selection for all concrete mix designs within this study source LCI data and match the National Ready-Mix Concrete Association (NRMCA) Industry wide EPD.

Construction

Stage A5 – Construction and Installation was not considered in this LCA study. Tally does allow manual inputs of construction impacts in MJ, kBtu, or kWh units, but current industry data is lacking on this subject. Environmental impacts realized in construction include labor, labor transport, waste disposal, crane operations, and construction materials such as shoring and formwork. These are all specific to the conditions of the site and systems to be installed. Speed and ease of construction focus on building costs but should also be considered to benefit embodied carbon reductions. Less crane time and general site activities will affect Stage A5.

A 1996 British case study concluded that Stage A5 varied between 5-9% of the total GWP of a 50,000 ft^2 office building, comparing wood, steel, and concrete systems (Cole & Kernan, 1996). The wood system was reported to require the least amount of energy to construct, then concrete, then steel. More studies of construction impacts should be explored and understood by the industry to further contribute to embodied carbon science and therefore, pathways to reduction.

Architectural Elements

Vertical enclosure, ceiling, and roof enclosure impacts were analyzed for this comparative study. The intent was to illustrate the relative embodied carbon impact of architectural versus structural elements and to capture the reduced vertical enclosure height for the concrete building. Majority of the architectural materials are defined using LCI data and industry average EPDs. When representative U.S. data was not available in Tally specific product EPDs were selected to represent architectural materials. These product EPDs were not rigorously studied to verify Stage A1-A3 inclusions, therefore the potential imprecision of the architectural impacts should be acknowledged.

Platte Fifteen Fly Ash Content for LCAs

Concrete Element	Fly Ash Content	Minimum Strength (psi)
Foundation - Pier Cap, Mat Slab, etc.	30-39%	5000
Columns	30-39%	5000
Core Walls	30-39%	5000
SOG	0-19%	4000
Elevated Slab	0-19%	5000
Topping Slab	0-19%	5000

Table 2. The specified fly ash content and compressive strength of the concrete used for each building LCA.

End of Life

As waste reduction, circular economies, recycling and reuse become more commonplace, analysis of the cradle-to-grave life cycle of a material, product, or building is crucial. Commonly, LCAs and EPDs report cradle-to-gate, Stage A1-A3. Tally completes the cradle-to-grave assessment using LCI data for Stage C and Stage D. Disposal (landfilled), reuse, and recycling mixes are assumed for each material based on industry averages. The end-of-life mix assumptions of the mass timber products were previously described in the context of biogenic carbon cycle. The steel shapes and mild steel reinforcing of this study are assumed to have 98% recovered (100% scrap) and 2% landfilled, while concrete is assumed to have 55% recycled into aggregate (Stage D considers grinding energy) and 45% landfilled. Impact credit is given for recovered materials, due to their functional reuse and associated avoided burden. The end-of-life assumptions can significantly affect the net GWP impact of a material and building LCA, illustrating the importance that direct reuse and recycling have on embodied carbon reductions by avoided manufacturing impacts and continued carbon sequestration within wood products.

Specific EPDs and end-of-life assumptions used in this analysis can serve as an illustration of inaccuracies or inconsistencies that influence an LCA, the need for a deeper look into the EPDs and data selected, and the void to be filled within the industry and within databases. Structural and building LCA results and comparative studies will become more potent and accessible as product and manufacturer specific EPDs become more readily available, and the standardization of material, product, and building LCAs evolve. Until then, relative impacts can inform system and product selection, and significant "hot spots" within the assessments can be identified. On a system specific level, LCAs are powerful to quantify reductions when project modifications are made, or practical end-of-life pathways are examined.

Photo credit: Denver Infill, Ken Schroeppel

LCA Comparative Results and Discussion

The results of the three structural system cradle-to-grave LCAs are summarized in this section, primarily focusing on GWP. The mass timber system outperforms the steel and concrete alternates in GWP and use of renewable energy.

Figure 7 illustrates the material choice impacts on the total GWP of each building system. The concrete and steel building systems have a very similar GWP; the mass timber building system has approximately a 14% reduction in GWP compared to the other two. Because of the significant amount of below-grade structure in all three buildings (32-inch mildly reinforced mat slab and 10-inch-thick foundation walls, with 12-inch-thick mildly reinforced slabs at the main level and first level below grade), concrete dominates the embodied carbon of all three, almost entirely obscuring the impact of other material contributions to the GWP. To get a clearer idea of

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Photo credit: Denver Infill, Ken Schroeppel

the varying material contribution, Figure 8 compares the total GWP of the three structural systems including only the framing system material above the Level 2 podium slab (columns, framing, and floor plate).[9] For this portion of the structure, the mass timber sees a 70% reduction in GWP compared to steel, and a 76% reduction compared to concrete. The GWP impact of the mass timber framing system is due almost entirely to the 3-inch concrete topping slab with steel reinforcement, with the mass timber glulam framing and CLT floor panel contributing less than 1%

[9]All results presented "above the podium slab" include only the column, framing, and floor plate assembly of each framing system.
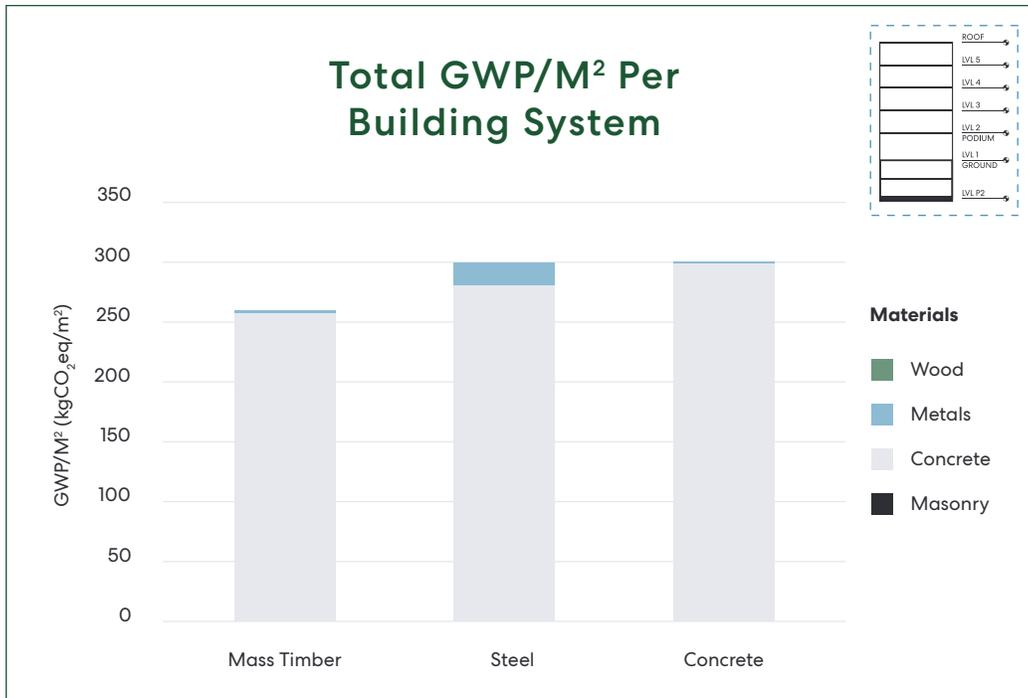
Figure 7. Total building GWP per square meter of each system with representative material contribution.
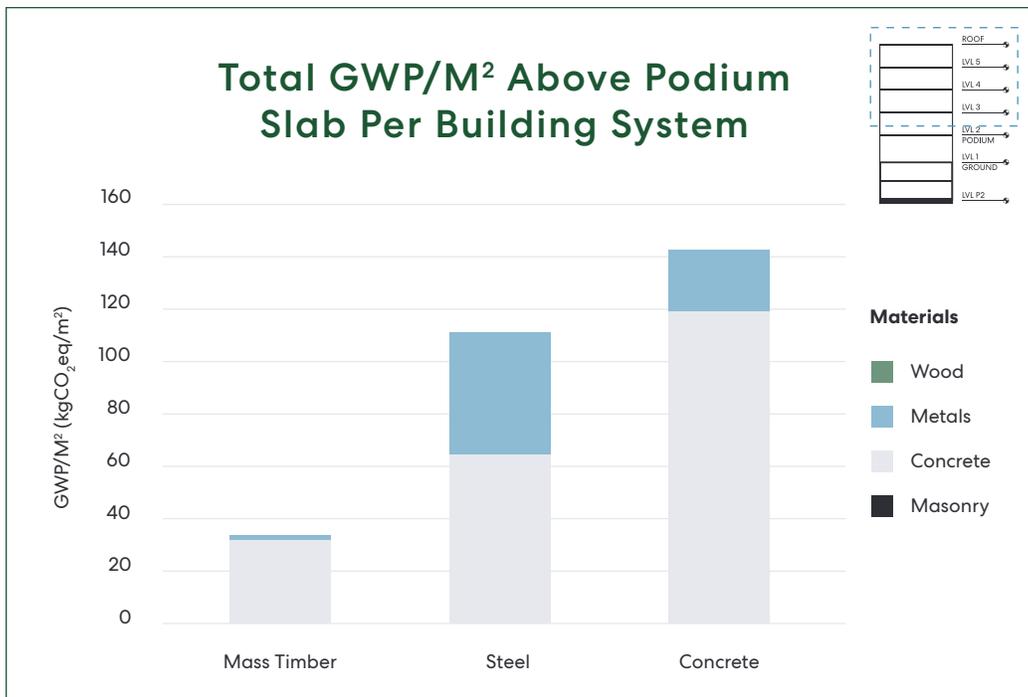

Figure 8. Total framing system GWP per square meter of each system with representative material contribution.

Figure 9 illustrates the contribution of each material to GWP in another way by showing the relative contribution of structural material quantities (SMQ) to the total building mass next to the corresponding relative GWP contribution of each material to the total GWP. Again, this figure includes only materials above the podium. Looking, for example, at the mass timber building, the figure shows that while the timber contributes 45% of the mass of the structure, it contributes less than 1% of the GWP. As material volume is reduced for both concrete and steel, GWP is reduced, and typically cost is reduced as well. A phenomenon of mass timber and biogenic carbon accounting is that as the wood material volume is increased, GWP is decreased due to greater carbon sequestration potential.
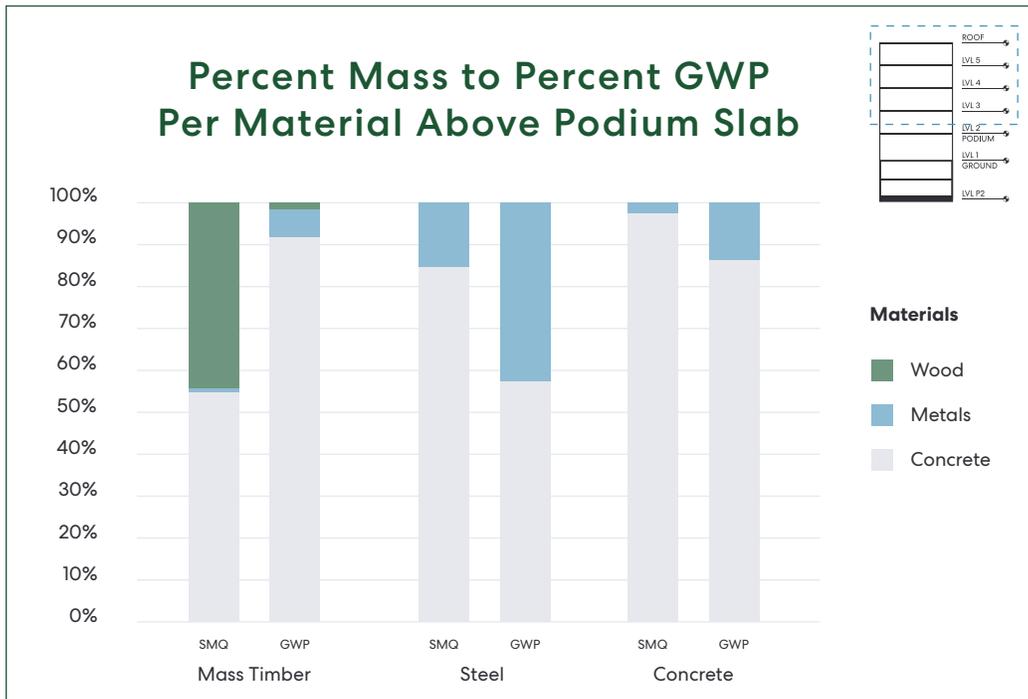

Figure 9. Relative contribution of materials to mass and to GWP of each system, above the podium slab.

The life cycle stages that most significantly contribute to global warming potential, embodied carbon, are those in Stage A – product extraction through manufacturing; this is illustrated in Figure 10. Due to biogenic carbon accounting, the mass timber system has a high GWP value at Stage C due to the assumed release of sequestered carbon at the time of demolition or deconstruction. End-of-life (Stage C and D) material impacts in this study are limited by the mix assumptions within Tally®.
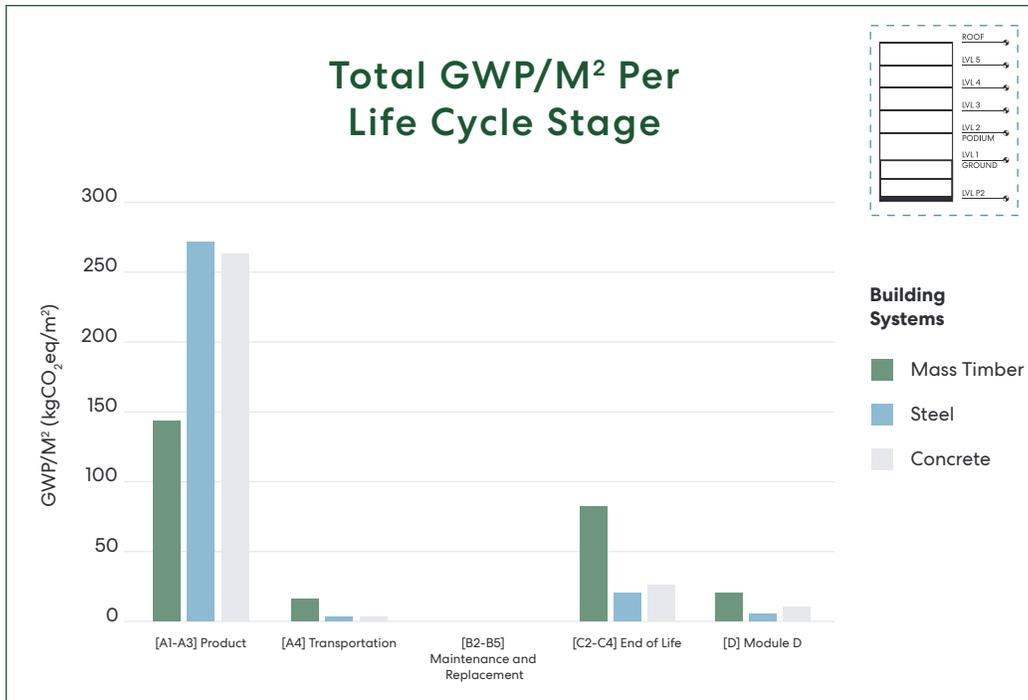
Figure 10. GWP contribution per square meter per life cycle stage of each building system.
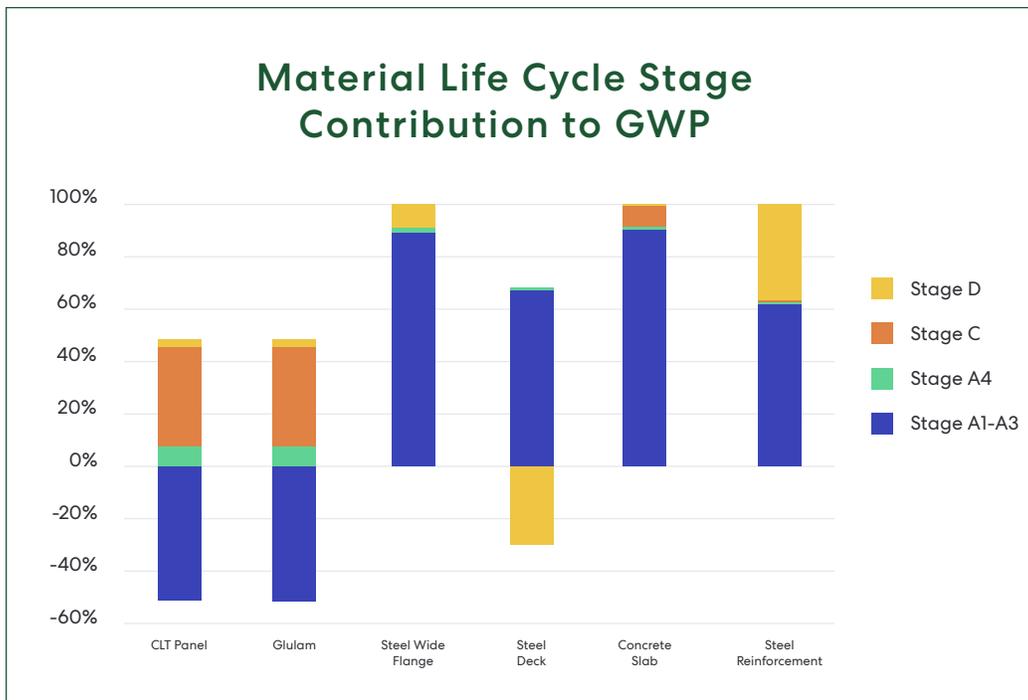

Figure 11. Relative GWP impacts of life cycle stage on the major structural materials.

The relative impacts of Stage A, Stage C, and Stage D on the major structural materials within this study are illustrated in Figure 11. Wood's carbon sequestration capability makes it the only current structural material that can realize negative GWP at Stage A. Steel can have negative GWP calculated at Stage C and D but are typically reduced by the energy required for processing the scrap materials. Steel deck realizes a negative impact at Stage D as 70% is assumed to be reused. Although that is a reasonable assumption for steel roof deck, recycling of steel deck in a composite concrete assembly is highly unlikely due to the practicality of separating the deck from concrete at the time of demolition. Tally assumes that all the metal deck in the composite concrete floors is recycled and does not allow user modifications of these assumptions, therefore the steel system GWP end-of-life impacts are artificially low.

The primary focus on global warming potential in this report is due to its potent impact on global temperature rise, compared to the other impact categories assessed by Tally. All calculated environmental impact categories are presented in Table 3.

Focusing on the reported mass timber product (glulam and CLT panel) impacts: Stage A1-A3, extraction through manufacturing is responsible for majority of the impacts regarding smog formation and energy demand, and roughly half of the impacts of acidification and ozone depletion potential. The remaining half are attributed to end-of-life, Stage C for acidification and the increased transport distance, Stage A4 for ozone depletion impact potential. Over 80% of the eutrophication potential occurs

at end-of-life, due to wood decomposition assumptions. Although the mass timber system requires more total energy demand, over 50% of that is renewable energy compared to the steel and concrete systems which utilize less than 7% renewable energy.

The environmental impacts of mass timber production are ascribed to combustion of wood and diesel fuel (across forestry operations, lumber production, and product manufacturing), electricity use, and adhesive/resin use and its transport (Binderholz Bausysteme GmbH, 2019) (Puettman, Sinha, & Ganguly, 2018).

The net negative ozone depletion impact for the concrete system is due to the recycling assumptions of steel reinforcement (rebar) and concrete at Stage D.

The results of this study show the mass timber framing system outperforming the steel and concrete systems in GWP and renewable energy use, but the steel and concrete systems perform better in the other reported impact categories. Other United States comparative studies of mass timber structures versus traditional materials, utilizing different LCI databases than Tally, found that mass timber systems have a lower impact on GWP, eutrophication, and ozone depletion, a similar smog impact, and utilize more renewable energy when compared to concrete (Gu & Bergman, 2018) (Pierobon, Huang, Simonen, & Ganguly, 2019).

Impact Category	Unit	Mass Timber	Steel	Concrete
Acidifcation	$(kgSO_2eq/m^2)$	0.96	0.43	0.41
Eutrophication	$(kgNeq/m^2)$	0.15	0.02	0.03
GWP	$(kgCO_2eq/m^2)$	34.39	113.53	141.71
Ozone	$(CFC-11eq/m^2)$	6.03E-06	8.62E-07	-6.20E-08
Smog	(kgO_3eq/m^2)	10.78	6.40	8.24
Energy Demand	(MJ/m^2)	2067.31	1127.52	1312.54
Non-Renewable Energy Demand	(MJ/m^2)	998.21	1152.61	1222.67
Renewable Energy Demand	(MJ/m^2)	1068.25	74.78	92.02

Table 3. The cradle-to-grave impacts of each system, including only the framing system material above the Level 2 podium slab (columns, framing, and floor plate).

Vertical enclosure, ceiling finish, and roof enclosure are presented separately from the structural system impact to allow consideration of architectural elements that may vary by structural system, impacting the aesthetic, acoustic performance, and fire ratings of the mass timber, steel, and concrete framing systems. The LCA of these finishes was performed based on the architectural construction drawings for Platte Fifteen. Figure 12 depicts the typical GWP impacts of these architectural assemblies per applied area (wall area, roof area, ceiling area). For example, if the GWP impact of additional ceiling finishes is desired in the instance of the steel and concrete framing systems, the increased impact can be understood by multiplying the additional finish area to the GWP impacts provided in Figure 12.
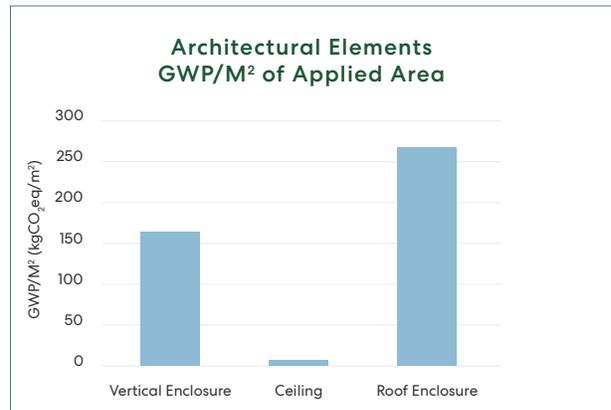
Figure 12 illustrates that exterior enclosure dominated the GWP of included architectural elements, and ceiling finishes had relatively low influence on GWP per applied area. Figure 13 represents the cumulative GWP of the architectural elements combined with structural, commonly referred to as a Structure plus Enclosure Life Cycle Assessment. The impact of ceiling finishes is equivalent for all three buildings. In reality, the steel and

Figure 12. Architectural element GWP per square meter of applied area.

concrete systems will likely call for additional finishes at the upper-level floor assemblies, further increasing their GWP impact compared to the mass timber system. The reduced building height of the concrete system, due to thinner structural floor thickness, produces a lower impact of vertical enclosure on the building GWP, compared to the mass timber and steel framing systems, although the structure remains the largest contribution.
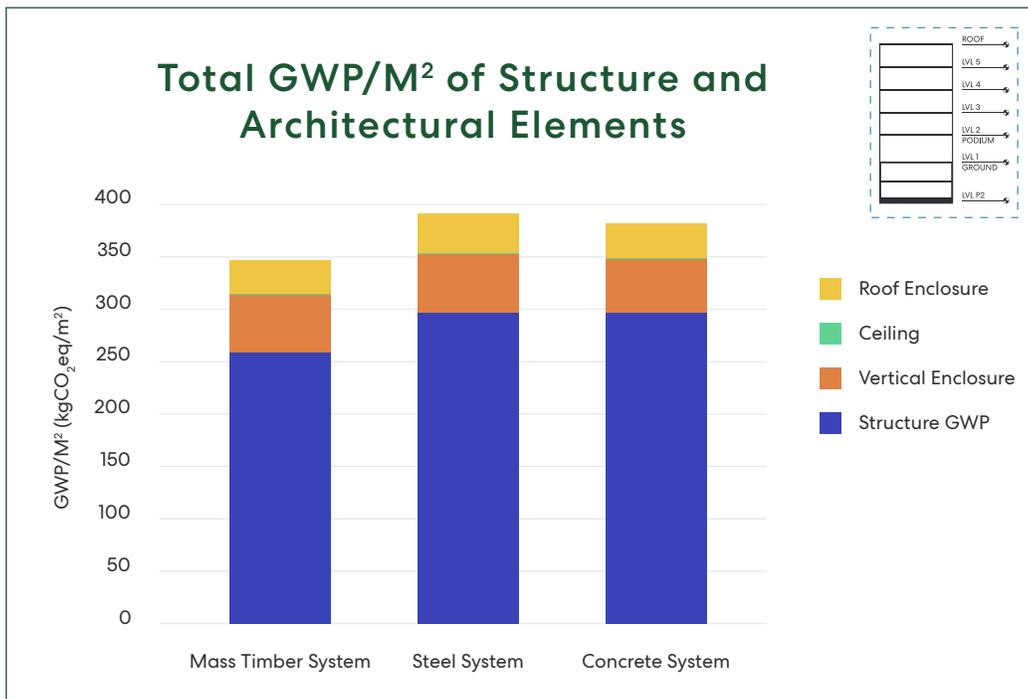

Figure 13. Structural plus architectural elements total GWP per square meter of each building.

Comparative Cost Study

This study focuses primarily on life cycle analysis and design choices in terms of embodied carbon savings. Building material choices obviously also have a cost in terms of dollars and time. Because the study was based on a constructed mass timber building that had been compared with a structural steel alternative at the time of the original design-development stage, these actual costs were available. The original contractor, Adolfson & Peterson Construction, agreed to share the cost comparison data and to prepare an estimate for the concrete version of the structure used in this study. In this way we can approach, at least for this one building, the question: what is the cost of sustainable material alternatives?

For the purposes of this analysis, the contractor used the actual constructed cost of the mass timber building and original pricing for the steel system, corrected to 2019 material and labor costs, and tied the price of the newly designed concrete alternative to unit prices from that same time period. The estimates include all concrete foundations and substructure, primary structure, topping slabs, and slabs on grade. The estimate also includes

exterior vertical enclosures, which was important to capture due to the lower floor-to-floor height of the concrete system, resulting in a lower enclosure cost. Special systems installed to protect the mass timber from the elements during construction were included in the cost estimates.

It often happens that initial pricing of mass timber systems shows a cost premium over conventional materials; this building was no different. The material cost premium of the mass timber structure is over 8% compared to the steel structure. Larger mass timber buildings can often be constructed in less time than concrete or steel. In this case, the contractor estimated that the mass timber structure could be erected 2 months faster than the steel, and 3.5 months faster than the concrete. (In the real structure, 6-8 laborers erected about 10,000 ft^2 of mass timber each week). The cost analysis took this into account by considering general conditions (labor), general requirements (equipment and waste), and crane costs. These compounding considerations reduced the premium for timber from 8.4% to 4.9% of structure cost.

Considered as a percentage of the whole building cost to the owner, the premium for mass timber was less than 2%. The premiums for mass timber and concrete over steel (the least cost alternative) are illustrated in Figure 14.

The structure cost relative to the whole building cost was very high (roughly 40%) due to the amount of sub-grade parking structure and foundations below groundwater. For a more typical, above grade structure, the cost premium of mass timber could easily be less than 1%. Taller structures, such as 9 story (Type IV-C) would also see more favorable cost comparisons due to scale efficiencies.

Builder's risk insurance for mass timber structures can be greater than comparable non-combustible structures. The variance of insurance premiums that were estimated at design development for Platte Fifteen for traditional non-combustible materials (concrete and steel) versus mass timber, translated to less than 0.16% of the total building cost. It should be understood that insurance premiums can differ for building types, conditions, and insurers. As a best practice, it is recommended to secure insurance premium quotes early in the design and costing process. General liability insurance premiums were not considered in this comparative study, as these costs were not carried by A&P.

There are other factors related to cost, time-cost, and return on investment that were not included in this study, but which benefited Platte Fifteen: early leasing, resulting from increased speed of construction, and lease rate. The exposed timber structure created a unique, biophilic built environment that allowed the offices to be leased at rates that were among the highest in the city at the time it opened; the building was 85% leased within one month of completion and lease rates were above any other low to mid-height office building in the Denver central business district. While it is not conventional at the time of this writing, carbon savings and impacts are expected to be directly related to dollar values. The small premium for the mass timber in this building could potentially be offset in whole, or in part by carbon credits.
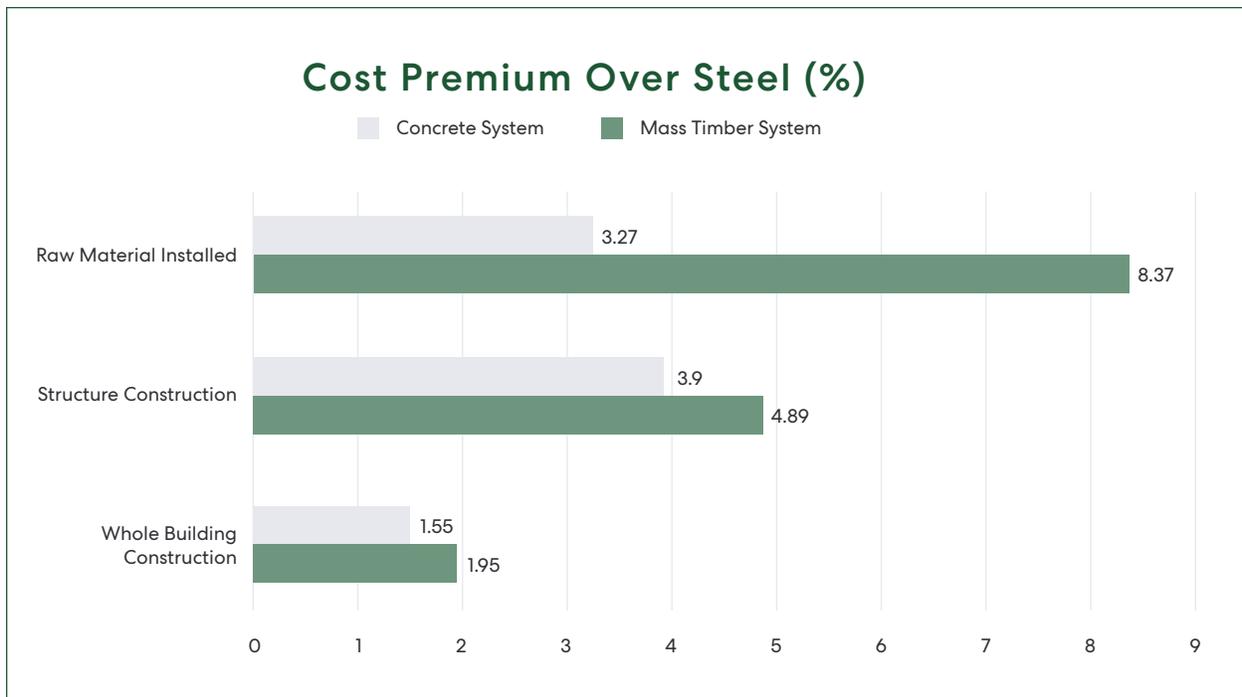
Cost Premium Over Steel (%)

Concrete System   Mass Timber System

Category	Concrete System	Mass Timber System
Raw Material Installed	3.27	8.37
Structure Construction	3.9	4.89
Whole Building Construction	1.55	1.95

Figure 14. Structural plus architectural elements total GWP per square meter of each building.

Conclusion

The LCA and cost data presented in this comparative study illustrate, for one specific case, the embodied carbon savings of mass timber structural systems that can be achieved with minimal cost impact (Figure 15). The results cannot be directly extrapolated to taller or differing building type applications, as these will be affected by structural proportioning, fire resistance requirements, and finish selection, but are clear enough to suggest similar positive results could be expected in a variety of building types.

Steel and concrete are the industry's structural champions and should be treated with respect and urgency as we seek innovative approaches to reduce their impact on building GWP; they will continue to be a part of our buildings. The use of mass timber to reduce GWP by sequestering carbon should also be increased, understanding that cost competitive solutions can be achieved with thoughtful design, material optimization, and thorough cost-estimating that includes the time savings as a real component of construction cost.

The simplest tactics to reduce GWP of building systems include program, layout, and design efficiencies – simply reducing material quantities through optimization. Bolder steps and multifaceted considerations are required to reduce the current industry's embodied carbon impact significantly. This includes pushing conventional structural materials to their minimal GWP impact, focusing on end-of-life pathways and direct material or building reuse, and implementing new material technologies. Such strategies will certainly face economic headwinds as innovative systems can be costly.

Realizing the capability of mass timber and its potential contributions to reducing embodied carbon is an opportunity for the building industry to make amends with our natural environment.
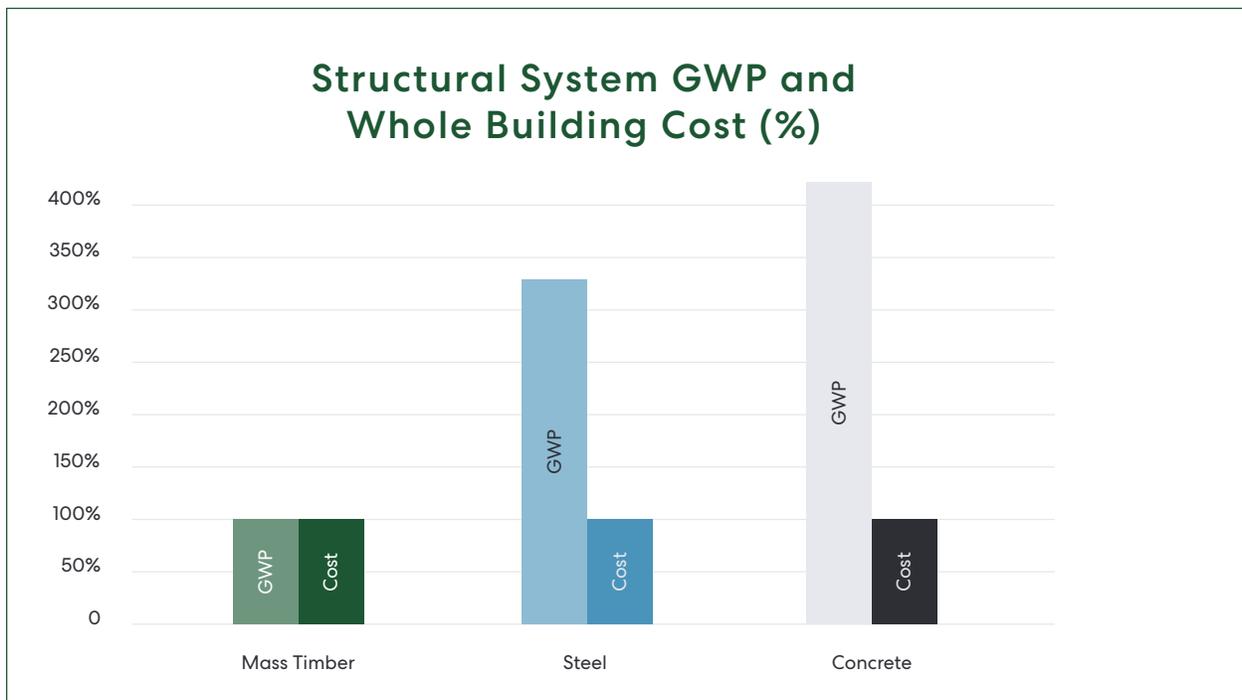

Figure 15. Comparison of the structural system GWP above the level two podium slab and the whole building cost of the three systems.

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They can be reviewed on the Think Wood website, <u>here.</u>

The "Material Category" provided in the Structural Material Quantities schedule is the material selection within Tally for either an EPD or LCI dataset. Category names that contain "EPD" are either industry average EPDs or manufacturer specific EPDs, typically with LCI data for Stages beyond A3. Category names that do not contain "EPD" are LCI dataset selections for all cradle-to-grave stages. Specific EPD and LCI data can be provided upon request. The "Sum of Mass Total" is the total mass in kilograms per material.

Tally® Calculation Methodology, Life Cycle Stages, Environmental impact Categories, and End-of-Life LCI data summary is provided, as well as Tally® LCA Report summaries for the three buildings in mass timber, steel, and concrete and Report summary for the included architectural finishes.

Appendix