Denver Office

Comparative Life Cycle Assessment Study

Author: KL&A Engineers & Builders

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Executive Summary

How does mass timber compare to traditional structural systems? Is mass timber sustainable? What are the associated dollar cost premiums?

This study of Denver Office, a commercial office building in Denver, Colorado, endeavors to answer these questions. It compares two functionally equivalent[1] structural systems—mass timber and steel—and the associated architectural systems in terms of global warming potential (GWP), dollar cost, and construction schedule. It is part of the *Mass Timber Comparative Life Cycle Assessment Series* comparing functionally equivalent structural systems across a variety of building types and geographic locations in the United States, and should be read together with the *Mass Timber Life Cycle Assessment Series Introduction* (Feitel & Kingsley, 2024).

The design team for Denver Office includes architecture firm Shears Adkins Rockmore (SAR+), structural engineer KL&A Engineers & Builders, and construction partner PCL Construction. The design was completed through the Design Development phase and the project has not been constructed. The reference mass timber building is Type III-A and four stories with a total area of 98,280 gross ft^2 (9,130 m^2). There is no below-grade construction, and the structure consists of shallow spread footing foundations with rammed aggregate pier ground improvement, slab-on-grade at the ground level, and four levels of mass timber (Level 2 to the roof). The alternative steel system is Type II-A concrete on metal deck supported by composite wide-flange framing and HSS steel columns, which is typical of similar office buildings in the Denver market.

Key results of this building study, which incorporates whole building life cycle assessment (WBLCA) by KL&A Team Carbon and construction cost estimates for both buildings by PCL Construction, include the following:

Global warming potential (cradle-to-grave): Considering only the structural components above grade (not including foundations or slab-on-grade), the LCAs show that the mass timber system GWP is 41 $kgCO_2eq/m^2$, which is 63% less than the steel system's GWP of 113 $kgCO_2eq/m^2$. The major contributors to GWP in the mass timber system are the concrete topping slab on Level 2 through Level 4 and the precast concrete cores. The contribution of the mass timber material is minimal due to the natural ability of wood to store carbon; this type of carbon (derived from material of biological origin) is termed biogenic carbon.[2]

The total GWP of the mass timber building is 140 $kgCO_2eq/m^2$, which is 42% less than the steel building GWP of 239 $kgCO_2eq/m^2$ (Figure 1). This savings is equivalent to 217 gas-powered passenger vehicles driven for one year or the electricity needed to power 180 homes for one year (United States Environmental Protection Agency, 2024).

Construction duration: The general contractor estimated that, for this building on this site in Denver, the mass timber system would be constructed 2.5 months faster (14% faster) than the steel system. This time savings benefits both the dollar cost and embodied carbon construction impact of the mass timber system.

Construction cost: It is common for initial cost estimates to show a significant material premium for mass timber over traditional structural materials, and Denver Office was no different. Comparing only the structural material costs, the mass timber system showed a striking 126% premium over steel. However, when considering the whole building construction cost, including cost savings associated with the shorter construction duration and variation in fireproofing and finish materials, the mass timber building is cost-neutral compared to the steel building. (Figure 2).

The construction industry has a significant opportunity and responsibility to address climate change by virtue of its outsized 42% contribution to global greenhouse gas (GHG) emissions (Architecture 2030, n.d.). The most immediate way for the building industry to reduce GHG emissions is to reduce embodied carbon—i.e., the emissions associated with physical building materials, through their raw material extraction, production and manufacturing, transportation, installation, and end-of-life scenarios. Mass timber structural systems are one potential strategy for embodied carbon reduction due to the material's relatively low manufacturing GWP impacts and its natural ability to store biogenic carbon for the life of a building (and potentially indefinitely).

This building study demonstrates that for projects like Denver Office, mass timber systems are a viable, cost-competitive approach to significantly reducing and minimizing a building's embodied carbon impact (Figure 2), with the understanding that building life expectancy, material sourcing,[3] and end-of-life pathways influence cradle-to-grave results.[4]

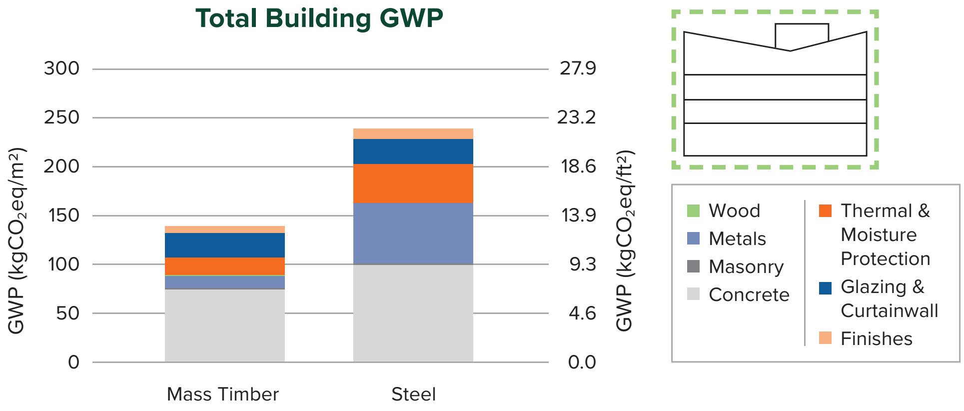


FIGURE 1: Total building (structure and architecture) GWP comparison and material contributions

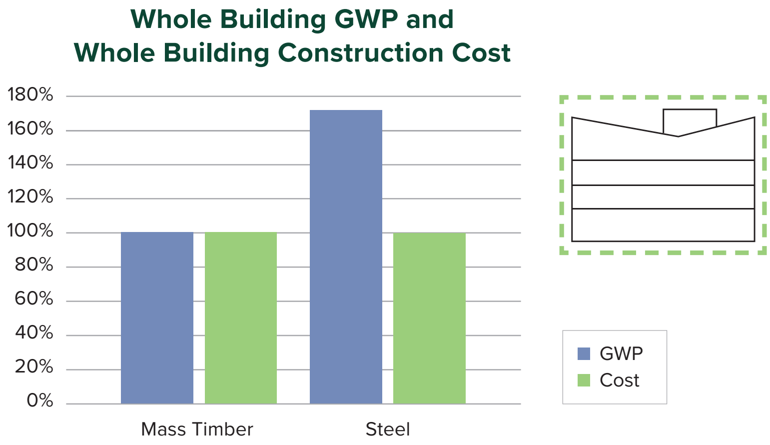


FIGURE 2: Total building GWP (structure and architecture, including the enclosure, fire resistance-rated assemblies, acoustic assemblies, and interior ceiling finishes) and whole building construction cost comparison of the building systems, normalized to the GWP and cost of the mass timber system

Introduction

The purpose of this building study is to use whole building life cycle assessment (WBLCA) and cost estimates to understand the embodied carbon and dollar cost differences between functionally equivalent[1] mass timber and steel structural systems. It compares Denver Office, a mass timber reference building located in Denver, Colorado, to an alternative building designed in steel. Comparisons between the two systems are made in terms of embodied carbon, construction dollar cost, and speed of construction. The variations in architectural designs (construction type, enclosures, fire protection, acoustic performance, and ceiling finishes) between the two buildings are included in the analyses.

This report starts with an overview of the reference mass timber building and alternative steel building, followed by the study scope, and then the results of the comparative life cycle assessments (LCAs), dollar cost, and speed of construction analyses. It is part of WoodWorks' *Mass Timber Comparative Life Cycle Assessment Series*, and is intended to be read together with the *Mass Timber Life Cycle Assessment Series Introduction* (Feitel & Kingsley, 2024). The series introduction details aspects common to all studies in the series including methodology, approach, scope, and code compliance of the comparative designs, LCA, and dollar cost analyses, and the importance of embodied carbon and biogenic carbon[2] as part of the building industry's strategy to address climate change and environmental degradation. This study details information specific to Denver Office and any variations from the series introduction.

Project Background and Alternative Designs

This section describes the reference building, design considerations for the alternative systems, and the structural and architectural design results.

This building study compares two structural systems for an office building: mass timber and steel. A steel system was chosen for comparison because it is the most viable alternative based on common construction practices for this type of project in the Denver market. The reference mass timber building is Type III-A construction and four stories.

The design team includes Shears Adkins Rockmore (SAR+) as Architect of Record, KL&A Engineers and Builders (KL&A) as Structural Engineer of Record, and construction partner PCL Construction.

The design of Denver Office was completed through the Design Development (DD) phase and the authors made use of the DD documents. The documents indicated that the cross-laminated timber (CLT) and glued-laminated timber (glulam) would be supplied by Nordic Structures from their plant in Chibougamau, Quebec, Canada.

Comparative Building Systems

The two building systems compared in this study were designed by KL&A in collaboration with the project architect, SAR+ (Figure 3).

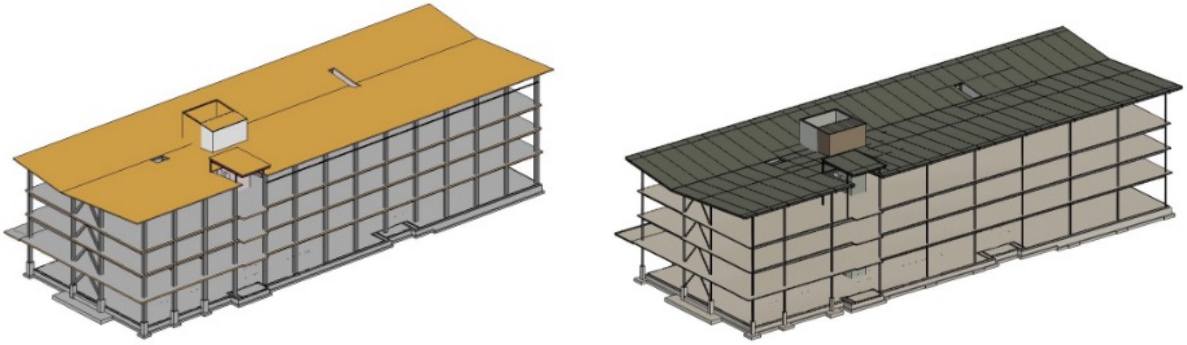


FIGURE 3: Schematic 3D images of the two alternate buildings—mass timber (left) and steel (right)

Reference Building – Mass Timber Building System

The mass timber reference building has a total gross floor area of 98,280 ft^2 (9,130 m^2) and includes four levels above grade and no below-grade construction. Level 1 is retail, restaurant, and back-of-house storage space. Levels 2 through 4 are office space. See Figure 4 for a schematic building section and Figure 8 for the typical office floor plan.

The foundations consist of 8-in. cast-in-place concrete stem walls on spread footings and 30-in.-thick mat slab foundations with 10 psf reinforcement under the core walls and braced frame. The mat slab foundations for the cores are isolated from one another. A rammed aggregate pier system is used for ground improvement due to soft soils and undocumented fill at the site, making it unsuitable to support foundations and floor systems in its current condition. Continuous spread footings are 1 ft thick and either 3 ft or 4 ft wide. Isolated footings vary in size from 4 ft x 4 ft x 1 ft thick to 8-ft-2-in. x 5 ft x 1-ft-6-in. thick. Level 1 is a 5-in.-thick concrete slab-on-grade.

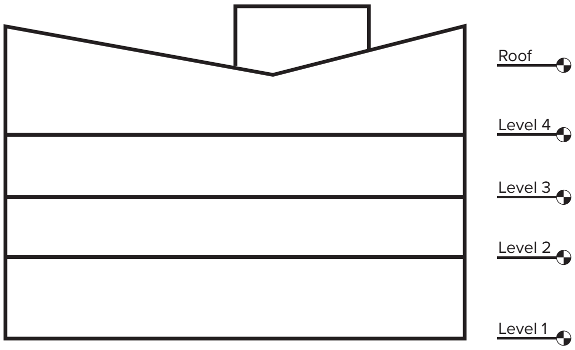
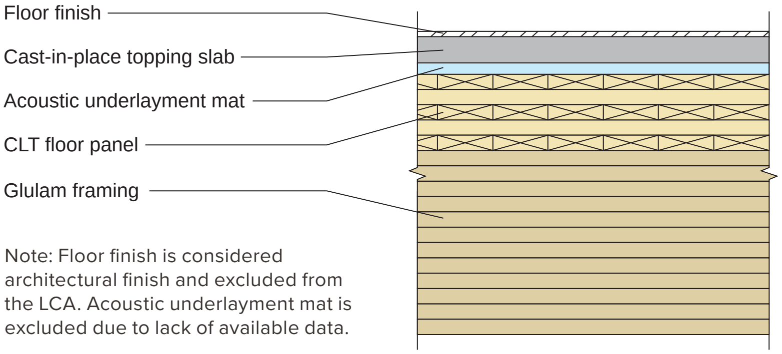


FIGURE 4: Schematic building section of Denver Office

Level 2 through Level 4 are mass timber, which can generally be described as a post, beam, and plate framing system with beams framing in one direction. The floor assembly consists of floor finishes on a 3-in. cast-in-place concrete topping slab over a 3/4-in. acoustic underlayment mat over 5-ply (6-7/8-in.- thick) CLT floor panels supported by glulam beams and columns (Figure 5). The concrete topping slab and acoustic underlayment mat are used to meet the sound transmission class (STC) and impact insulation class (IIC) specifications of 56 and 54 respectively, allowing the CLT panels to remain exposed at the underside. Glulam beams are between 6-3/4 in. and 14-1/4 in. wide and 12 in. to 27 in. deep. Glulam columns are 16 in. wide x 24 in. deep. At the restaurant/retail space on the south end of the building, there are exterior exposed glulam columns at the first level; these will be manufactured with Alaskan cedar. The grid system is typically 20x34 ft (6.1x10.4 m) at exterior bays and 20x22 ft (6.1x6.7 m) at the interior bay. The glulam beams span 34 ft and cantilever from both exterior bays of the building into the short 22-ft bay, creating a 5-ft-wide “mechanical highway” with no interruption by glulam framing (Figure 6). This is possible because of the two-way spanning capability of CLT panels.



Note: Floor finish is considered architectural finish and excluded from the LCA. Acoustic underlayment mat is excluded due to lack of available data.

FIGURE 5: Mass timber system floor assembly

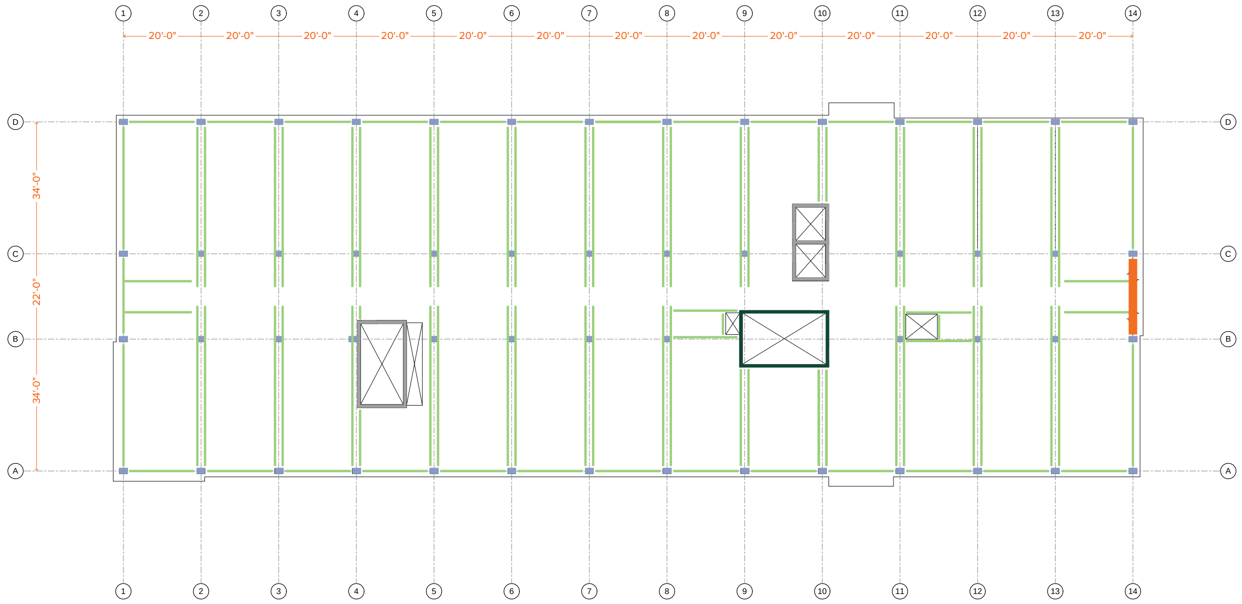


FIGURE 6: Mass timber reference building typical floor office floor plan

The typical roof consists of 5-ply (6-7/8-in.-thick) CLT panels supported by glulam beams, which also span in one direction. The CLT roof panels are exposed at the interior and topped with a vapor barrier, board insulation, cover board, and weather barrier (Figure 7). At the occupiable roof deck on Level 2, the CLT panels are topped with a weather barrier and a precast concrete paver pedestal system. The roof has 8-in. concrete rainwater retaining walls in two locations. Photovoltaic (PV) panels on raised metal strut framing are fastened directly to the CLT panels.

Denver is in a region of low seismicity and moderate winds with an ultimate design wind speed of 115 mph. The lateral design of the reference mass timber office building is governed by wind in the east-west direction and seismic in the north-south direction. The lateral system is comprised of two 10-in. intermediate precast cores at the elevator and stair cores and a single glulam braced frame oriented in the east-west direction. There is another core comprised of 7-ply (7-3/4-in.) CLT walls, which is not used for lateral resistance and supports gravity loads only. The pop-up roofs over the stair and elevator cores consist of 5-ply (6-7/8-in.) CLT panels.

The vertical enclosure finish is a combination of windows and curtain wall systems, metal composite material (MCM) panel, concrete masonry unit (CMU) veneer, and stone veneer. The finishes are backed with a layer of exterior board insulation, a fluid-applied air and water-resistive barrier, and 5/8-in.-thick exterior fiberglass mat gypsum board. The exterior wall is framed using platform-framed non-load-bearing cold-formed steel studs with glass fiber batt insulation in the stud cavities and fire-resistant gypsum board at the interior face.

Interior partition wall assemblies consist of cold-formed metal studs with glass fiber batt insulation filling the spaces between the studs and one or two

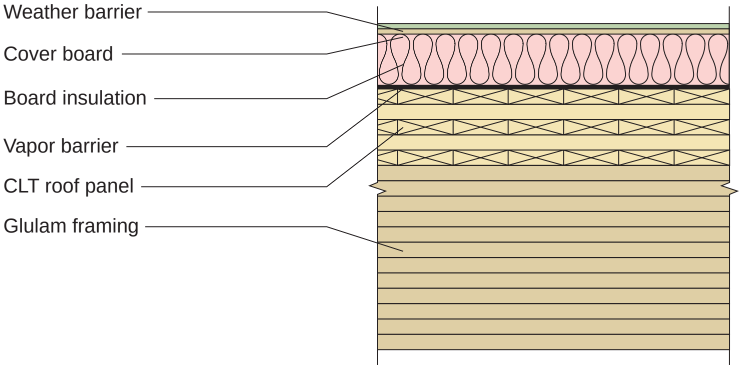


FIGURE 7: Mass timber system roof assembly

layers of 5/8-in. gypsum board on each face. There are no interior load-bearing walls except the core walls.

The mass timber building is Type III-A, which requires a 1-hour fire-resistance rating (FRR) of the primary structural frame, floor, roof, and interior bearing walls as referenced in Table 601 of the International Building Code (IBC). Interior non-bearing walls are typically allowed to have a 0-hour FRR in Type III-A buildings, with framing corridors and exit routes requiring either a 1-hour or 2-hour FRR depending on the number of stories connected. Exterior walls that are non-bearing require a 0 or 1-hour FRR depending on their fire separation distance. Glulam beams and columns and the underside of CLT panels are typically exposed. Their FRR is achieved by ensuring that wood members are sized adequately to achieve a char layer in the event of a fire while maintaining their structural adequacy.[5] The CLT core walls meet FRR requirements through the inclusion of a designed char layer and the precast walls utilize the inherent fire resistance of concrete and reinforcement cover requirements.

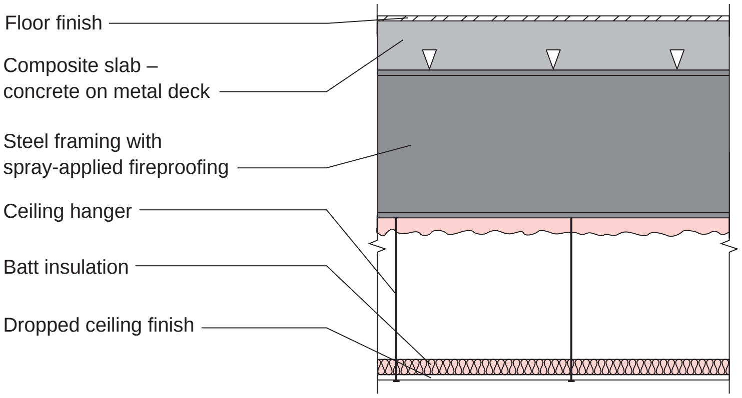
Most CLT panels are exposed at their underside; however, the private offices have dropped acoustic ceiling tiles, and restrooms, corridors, and communal workspaces have dropped gypsum board ceilings. Both the acoustic ceiling tiles and gypsum board are hung from the floor or roof CLT panels with a suspended grid ceiling system. The exit corridor at Level 1 has a rated gypsum board ceiling assembly.

Steel Building System

The alternate building is functionally equivalent and meets the same design criteria as the reference mass timber building, meaning equivalent floor area, site orientation, programmatic layout, geographic location, load criteria, and performance requirements, in accordance with ISO 14044 4.2.3.7 and ASTM E2921.

The foundation system is the same as the mass timber building, with modifications to location, quantity, and size of foundation elements based on the column layout and weight of the structure, which is roughly 11% heavier than the mass timber building. All continuous footing thicknesses increase by 4 in. (16 in. total) to support the increased weight. There are 35% fewer isolated footings in the steel building compared to the mass timber building due to the altered structural grid system. The thickness of the isolated footings increases by 4 in. (22 in. total) throughout due to a 40-50% increase in column loads. The concrete slab-on-grade thickness and extent is identical to the mass timber building.

The concrete mat slab foundations supporting the three cores and braced frame differ in geometry and size from the mass timber building. The mat foundation under the stair core that is used laterally in both the mass timber and steel buildings increases in thickness by 2 in. (32 in. total) and the reinforcement increases by 1 psf to 11 psf. A single 30-in.-thick mat foundation extends under both the elevator and other stair core, with 10 psf steel reinforcement.



Note: Floor finish is considered architectural finish and excluded from the LCA.

FIGURE 8: Steel system floor assembly

The thickness of this mat slab is the same as in the mass timber building. However, because this stair core is being used to resist lateral loads, the footing size increases by 64% to extend under both the elevator and stair core. The mat foundation under the braced frame decreases in thickness by 6 in. (24 in. total) and reinforcement by 2 psf to 8 psf. This is because the braced frame takes less lateral load than in the mass timber system due to the use of a third lateral core.

The steel system in Level 2 through Level 4 can generally be described as a post-and-beam framing system. The floor assembly consists of floor finishes on 6-in.-thick composite slab comprised of 4-in. normal weight cast-in-place concrete over a 2-in. 20-gauge steel deck (Figure 8), supported by composite wide-flange steel beams and girders spanning to HSS steel columns. Typical beams are 18 in. deep at exterior bays and 12 in. at interior bays. Girder depths range from 18 in. to 24 in. HSS columns are 8 in. wide x 8 in. deep.

The structural grid was modified from that of the mass timber system—from 20x34 ft to 30x34 ft at exterior bays and 20x22 ft to 30x22 ft at the interior bay to align with conventional steel spans (Figure 9). The “mechanical highway” routing strategy is the same as in the mass timber system; however, due to the one-way spanning capability of the composite deck, the interior bay is framed with 12-in.-deep wide-flange beams, which increases the depth of the overall floor system. The exposed underside of the metal deck presents acoustic and aesthetic concerns, requiring dropped ceiling assemblies hung from the wide-flange steel beams and girders with ceiling hangers. The exterior columns of the steel building are not exposed but instead wrapped in an assembly consisting of exterior sheathing, an air and weather barrier applied over the exterior sheathing, and metal composite panel supported on a metal-framed girt system.

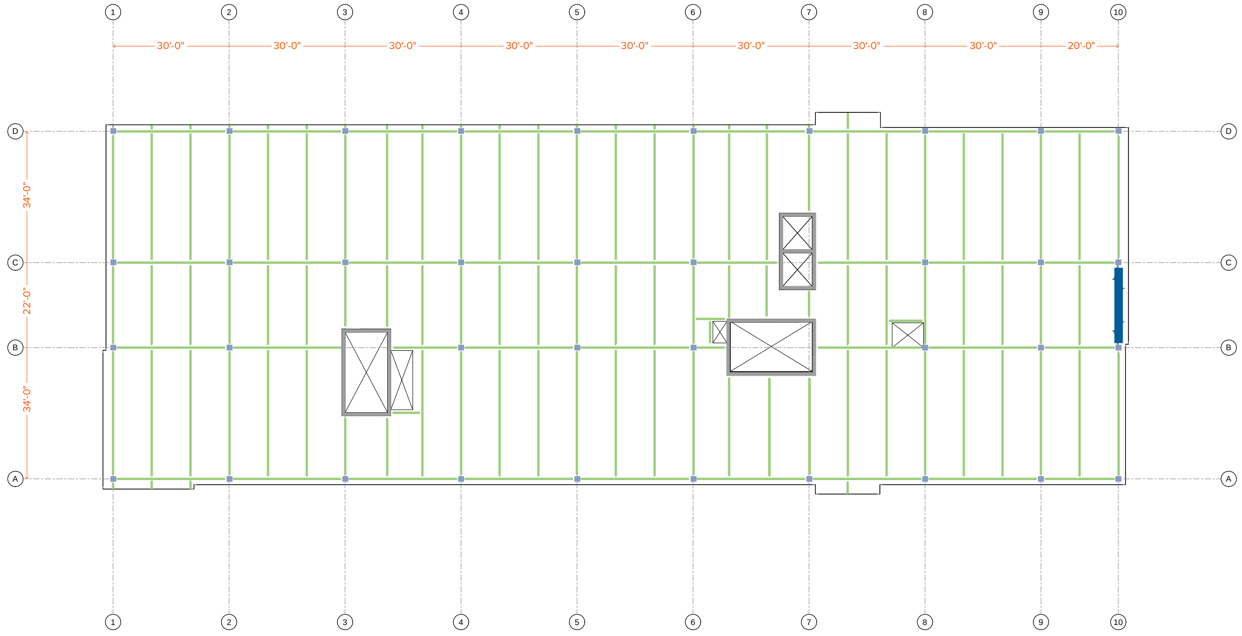


FIGURE 9: Steel building typical office floor plan

▬ Structural Column Locations

▬ Structural Framing Locations

▬ Precast Concrete Core Wall

▬ Steel Braced Frame

The typical roof assembly consists of a weather barrier, cover board, board insulation, a vapor barrier, and gypsum sheathing board on top of 3-in. 20-gauge metal roof deck, supported by non-composite wide-flange steel beams and girders spanning to HSS steel columns (Figure 10). This structural system was selected instead of the more common system of open-web steel joists for flexibility and adaptability of the PV panel array attachment. The occupiable roof deck on Level 2 has the same assembly as the mass timber system, except 6-in.-thick composite deck is used instead of CLT panels. The concrete rainwater retaining walls and PV panels are the same as in the reference mass timber building, with PV panels supported by raised metal strut framing fastened to the wide-flange framing through the metal roof deck.

Because the steel building has slightly higher story forces than the mass timber building due to its increased seismic weight, all three cores are utilized as lateral load-resisting elements. Matching the mass timber building, the precast stair and elevator cores in the steel building act as lateral load-resisting elements and have the same geometric layout. Additionally, the CLT panel stair core is replaced with 10-in. precast concrete walls, which are used for lateral resistance. The glulam braced frame is replaced with a steel ordinary concentrically braced frame. The pop-up roofs over the stair and elevator cores differ from the mass timber building in that they are composed of 3-in. 20-gauge roof deck supported by non-composite wide-flange beams or cold-formed steel joists spanning to precast concrete walls or HSS columns.

Both the vertical enclosure and interior partition wall locations and assemblies are unchanged between the steel and mass timber buildings.

The steel building is Type II-A construction, requiring a 1-hour FRR on the primary structural frame, floor, roof, and interior and exterior bearing walls as referenced in IBC Table 601. Interior non-bearing walls are typically allowed to have a 0-hour FRR in Type II-A buildings with framing corridors and exit routes requiring either a 1-hour or 2-hour FRR depending on the number of connected stories. Exterior walls that are non-bearing require a 0 or 1-hour FRR depending on their fire separation distance. To achieve fire protection, spray-applied cementitious fireproofing is applied to all steel beams and columns, including the steel braced

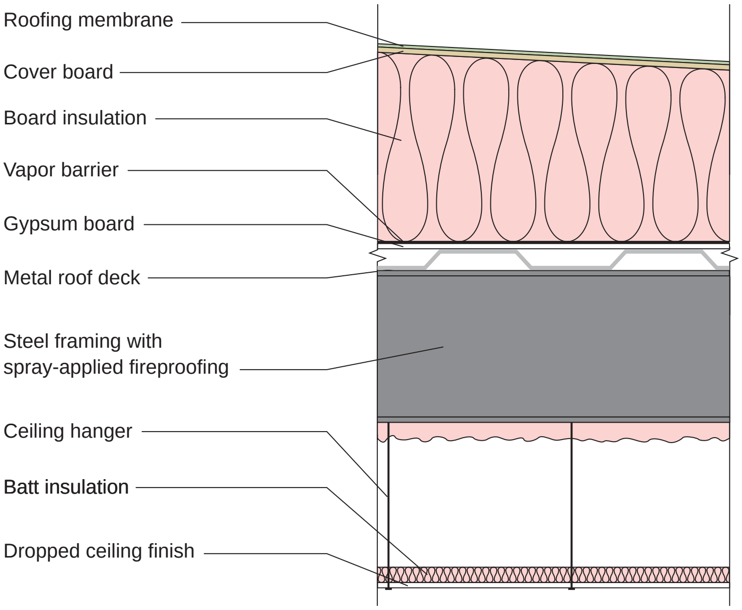


FIGURE 10: Steel system roof assembly

frame in alignment with standard practice for office buildings in the Denver market. The concrete slab-on-metal deck assembly meets the 1-hour FRR requirements without the need for additional fireproofing materials. The precast core walls utilize the inherent fire resistance of concrete and reinforcement cover requirements to meet the needed FRR.

The ceiling assemblies vary between the two buildings to meet the same STC and IIC performance requirements. While the underside of CLT is typically exposed in the mass timber building, dropped ceilings are much more prevalent in the steel system for equivalent acoustic performance. Suspended gypsum board ceilings are used throughout the ceilings of Level 2 to the roof, with exposed metal deck only in back-of-house locations. Suspended acoustic ceiling tiles are present in offices, matching the mass timber system. The exit corridor at Level 1 has a rated gypsum board ceiling assembly matching the mass timber building. Because the tenant of the Level 1 retail space is unknown, aesthetic assumptions regarding the ceiling assemblies were avoided so as not to increase the steel building's GWP; the underside of the metal deck and steel framing is assumed to be exposed, like the CLT.

Building Floor-to-Floor Heights

The floor and roof assemblies and structural framing depths vary between the mass timber and steel systems, with floor-to-floor height requirements as determined by the project architect, considering dimensional constraints and comparable aesthetics, views, and daylighting specific to each system. The 18-ft floor-to-floor height of Level 1 to Level 2 remains unchanged between the two buildings; however, the floor-to-floor heights above Level 2 vary as shown in Table 1. The depth of the structural framing for the mass timber system is approximately 3-ft-2-in. The depth of floor framing in the steel system is about 2 ft, which is 1-ft-2-in. less than the mass timber system. The steel system, however, has dropped ceilings throughout the majority of the building extending roughly 1-ft-10-in. below the bottom of the steel framing to allow for up to 20-in. ducts to run below the steel framing, resulting in a total floor depth of 3-ft-10-in., or approximately 8 in. more than the mass timber floor assembly depth. To account for this difference, the finished floor to finished floor height of the steel system is increased by 8 in. from the mass timber system, resulting in a floor-to-ceiling height of 10 ft, comparable to that of the mass timber system. This impacts the height and material quantities of the vertical enclosure, vertical framing, and interior walls.

Floor Elevations and Building Height

Structural System	Floor-to-Floor Height	Floor to Ceiling[a]	Total Building Height
Mass Timber	13'-4"	10'-3"	63'-7"
Steel	14'-0"	10'-0"	65'-7"

[a] Floor to ceiling is defined as the top of finished floor to bottom of horizontal ceiling surface, either finished ceiling for steel or exposed structure for mass timber.

TABLE 1: Relative floor heights above Level 2 and total building heights of both systems

Concrete Mix Designs

Concrete is a high-embodied carbon material and its GWP impact often dominates a building's total GWP. A significant portion of concrete GWP is due to the cement content, and replacing cement with supplemental cementitious material (SCM) is one method for decreasing concrete's GWP impact. Table 2 lists the concrete mix designs' 28-day strength and SCM content per concrete element used within the two building LCAs. As explained in the series introduction, concrete mix design data in TallyLCA references the 2019 National Ready Mixed Concrete Association (NRMCA) *Industry-Average Environmental Product Declaration* (EPD), plus supplemental life cycle inventory (LCI) data.

The mix designs selected for this building study reflect the 28-day or 56-day strengths specified in the Denver Office DD documents. However, these documents utilize performance-based concrete specifications and do not dictate the exact mix design ingredients or SCM content to achieve lower embodied carbon concrete. The SCM content selected for this study is intended to be as optimistic regarding concrete GWP impact as could reasonably be assumed for material availability and common practice in the Denver market. The included SCM was fly ash (noted as FA in Table 2) per local practice. For this study, fly ash content was increased to a reasonable maximum while considering finish-ability and speed of construction. Concrete elements assigned 20% fly ash content were considered sensitive to finish requirements and sequencing of construction. The elements assigned 40% fly ash content were those for which it was acceptable to reach their specified strength beyond 28 days.

Many ready-mix suppliers in the Denver area have recently switched their cement supply from Type I/II Portland cement to Type IL Portland limestone cement. Due to the higher limestone content in Type IL, its embodied carbon impact can be reduced by 10% compared to Type I/II (Portland Cement Association, 2024). This potential reduction is not considered in the NRMCA industry-average EPD data. However, supplemental LCA results are provided to consider this impact in the section, Supplemental Life Cycle Assessment Results.

As explained in the series introduction, no precast concrete data set is available within TallyLCA, so cast-in-place concrete data is used as a proxy. This data underestimates the A1-A3 GWP impact by 33% when compared to the current Canadian Precast/Prestressed Concrete Institute's *North American Industry-Average* EPD (2019). This data also misrepresents the LCA stage of some GWP impacts. For example, embodied carbon associated with the pouring, curing, and formwork of the precast product occurs in Module A3; however, for the cast-in-place concrete data used, this impact occurs in Module A5. Module A5 is excluded from the scope of this study.

Concrete Mix Property Assumptions	
Element	**Concrete (psi, SCM%)**
SOG	4000, 20% FA
Columns	5000, 20% FA
Pilasters	5000, 40% FA
Mat Slabs	5000, 40% FA
Footings	5000, 40% FA
Foundation Walls	5000, 40% FA
Precast Shear Walls	6000, 40% FA
Slab on Metal Deck	4000, 20% FA
Topping Slabs	4000, 20% FA

TABLE 2: Concrete mix design assumptions for both buildings

Life Cycle Assessment Methodology

The methodology, approach, and code compliance of the individual LCAs and their comparisons are detailed in the series introduction. Major methodology and assumptions are described in this section, as well as variations from the general series.

Life Cycle Assessment Material Scope

The component and material scope of the LCAs includes primary structure, vertical and horizontal enclosures, fire resistance-rated assemblies, acoustic assemblies, and interior ceiling finishes as described in the section, Comparative Building Systems. As such, they are considered whole building life cycle assessments. Material quantities are based on the designed quantities at DD and do not consider final bill of materials or estimates for construction waste.

The primary structure includes substructure (foundations and slab-on-grade) and superstructure elements (gravity systems: floors, roofs, beams, columns, walls; lateral systems). Reinforcing steel within concrete elements is included.[6] Itemizing the slab-on-grade as part of the substructure varies from the series introduction. The purpose of this variation is to isolate the alternate structural systems of the superstructure and avoid dilution of their GWP comparison. The slab-on-grade's concrete and steel reinforcement quantities and resulting GWP impact are identical in the two buildings. Connections and accessory structural elements such as miscellaneous metals (elevator support, stairs, handrails) are excluded. Topping slabs and rainwater retaining walls at the roof are designated as structural scope for the purpose of the LCAs.

The vertical enclosure includes the exterior finish, windows and curtain wall systems, waterproofing, insulation, wall framing, fire protection materials, and gypsum board. Windows and curtain wall systems are categorized as openings and glazing, insulation is categorized as thermal and moisture protection, and all other architectural components of the vertical enclosure are categorized as finishes. The horizontal enclosure includes the exterior finish, precast concrete paver pedestal system where it occurs, waterproofing, insulation, framing, fire protection materials, and acoustic materials. Cementitious fireproofing applied to the steel beams and columns and insulation are categorized as thermal and moisture protection, while all other architectural items in the horizontal enclosure are categorized as finishes. The interior ceiling finishes include acoustic ceiling tiles, gypsum board, and suspended grid ceiling systems. These are categorized as finishes.

Load-bearing interior walls, such as the core walls in both buildings, are included in the LCA scope. Interior fire-rated wall and floor assemblies are included within the LCAs, whether they serve as structural members or not. Non-load-bearing interior partition walls that are not fire rated are excluded from the LCAs. Ceiling finishes, as noted in the building system descriptions, are included. All other interior architectural finishes (floor finishes, interior wall finishes, furnishings, paints, stains, sealers, etc.) are excluded. Fireproofing detailing at window heads and sills is also excluded.

Other exclusions are site work, civil, landscape, mechanical, electrical, plumbing, and all interior furnishings. The photovoltaic panels and their attachment are excluded from the LCA due to a lack of North American EPDs available for embodied carbon quantification of PV systems.

The foundation system for both buildings in this study relies on a rammed aggregate pier system for ground improvement. Rammed aggregate piers are a delegated design and material quantities were not determined for this analysis. For this reason and the fact that the pier system is categorized as site work and not primary structure, it is excluded from the scope of this LCA.

A noteworthy exclusion is the acoustic underlayment mat that is inherent to the CLT floor assembly to achieve the STC rating (Figure 5). At the time of this study, there are only a handful of EPDs available for acoustic underlayment mat products in North America. The *Return to Form Comparative Life Cycle Assessment Study* in this series explores the potential impact of acoustic underlayment mat and provides more information on this topic (Kehoe, Feitel, & Kingsley, 2024).

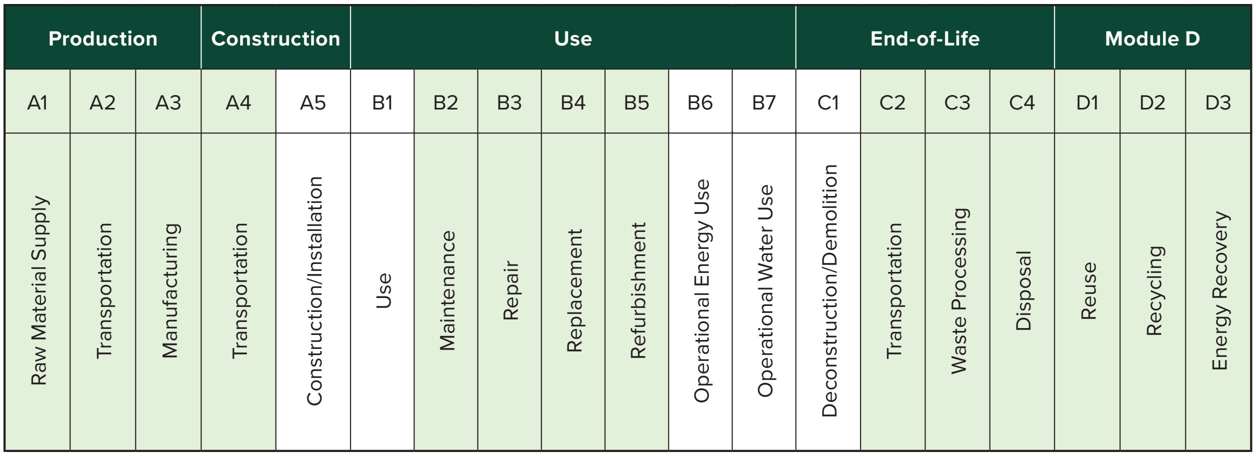
Life Cycle Assessment System Boundary

The LCA system boundary is cradle-to-grave (A-C plus D), inclusive of Modules A1-A3, A4, B2-B5, C2-C4, and Module D (Figure 11). The building's service life is 75 years, representing the reference study period. The service life for all materials and components match that of the building, except roof finishes and windows, which are assigned 40-year service lives.

Concrete carbonation is excluded.

Biogenic carbon flows are included. The methodology in TallyLCA dictates the end-of-life mix allocation assumptions. See the series introduction for more detail.

Life Cycle Stages:
Cradle-to-Grave + Module D



Production			Construction		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	Transportation	Manufacturing	Transportation	Construction/Installation	Use	Maintenance	Repair	Replacement	Refurbishment	Operational Energy Use	Operational Water Use	Deconstruction/Demolition	Transportation	Waste Processing	Disposal	Reuse	Recycling	Energy Recovery

Note that the stages and information modules shown here deviate slightly from the naming convention used in ISO 21930 (ISO, 2017). However, this series generally uses terminology consistent with ISO 21930.

FIGURE 11: LCA life cycle stages; scope inclusions in light green

Life Cycle Assessment Data Methodology

For the LCA data methodology, assumptions, data uncertainty, software limitations, and end-of-life methodology, reference the series introduction. The Supplemental Life Cycle Assessment Results section of this report addresses the data limitations within TallyLCA identified for glulam, CLT, and concrete mixes. See the Appendix for the specific material quantities and EPD and LCI data selections used to perform the individual LCAs.

The DD documents indicated that Nordic Structures would supply CLT and glulam for the project from their plant in Chibougamau, Quebec, Canada. The manufacturing plant is 2,450 miles (3,940 km) from the project location in Denver, Colorado. This transportation distance was considered in the LCA of the mass timber building.

There are several columns specified as Alaskan cedar glulam at the exterior of the mass timber building; however, there is a lack of available EPD data for Alaskan cedar glulam material and a supplier was not identified for this analysis. These columns are therefore assigned the same data set as typical glulam. Reference the series introduction for more information on the glulam data set within TallyLCA.

Comparative Results and Discussion

The LCA, cost, and speed of construction results of the building study are described in this section. The LCA results focus on GWP, measured in kilograms of carbon dioxide equivalent ($kgCO_2eq$). The results are presented in terms of $kgCO_2eq/m^2$ ($kgCO_2eq/ft^2$) based on the gross floor area of the building, which is the industry standard.

Life Cycle Assessment Results

Table 3 summarizes the WBLCA results, providing the GWP impact of the total building, isolating the superstructure and substructure, and breaking each down by structural and architectural systems.

When considering the total GWP impact of the building, including architectural and structural systems, the mass timber building has 42% less GWP than the steel building (Figure 12). The total GWP impact is 1,275,121 $kgCO_2eq$ (140 $kgCO_2eq/m^2$) for the mass timber building and 2,185,801 $kgCO_2eq$ (239 $kgCO_2eq/m^2$) for the steel building.

GWP Summary Table								
	Total Building			Superstructure			Substructure	
	Total	Structure	Architecture	Total	Structure	Architecture	Total	Structure
Mass Timber $kgCO_2eq$	1,275,121	782,235	492,886	870,360	377,474	492,886	404,761	404,761
Steel $kgCO_2eq$	2,185,801	1,458,333	727,468	1,756,465	1,028,997	727,468	429,337	429,337
Mass Timber $kgCO_2eq/m^2$ ($kgCO_2eq/ft^2$)	140 (13)	86 (8)	54 (5)	95 (9)	41 (4)	54 (5)	44 (4)	44 (4)
Steel $kgCO_2eq/m^2$ ($kgCO_2eq/ft^2$)	239 (22)	160 (15)	80 (7)	192 (18)	113 (10)	80 (7)	47 (4)	47 (4)

TABLE 3: Summary of GWP of the total building, superstructure, and substructure with contributions from structural and architectural systems

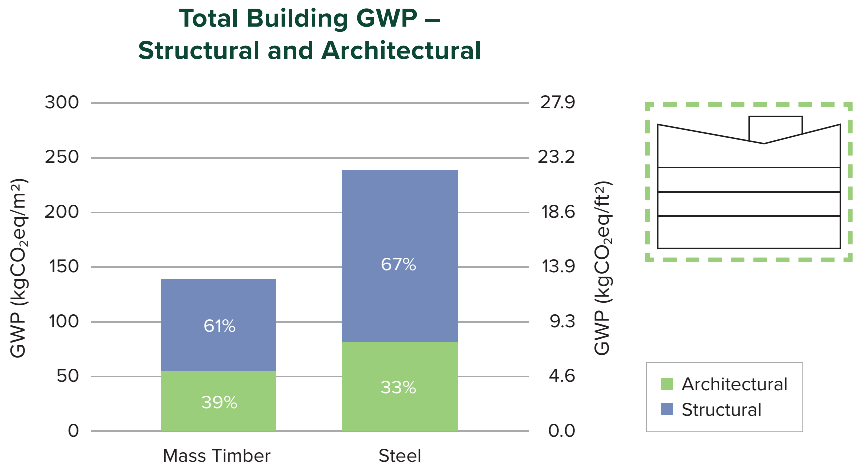


FIGURE 12: Total building GWP (structure and architecture) comparison of both buildings

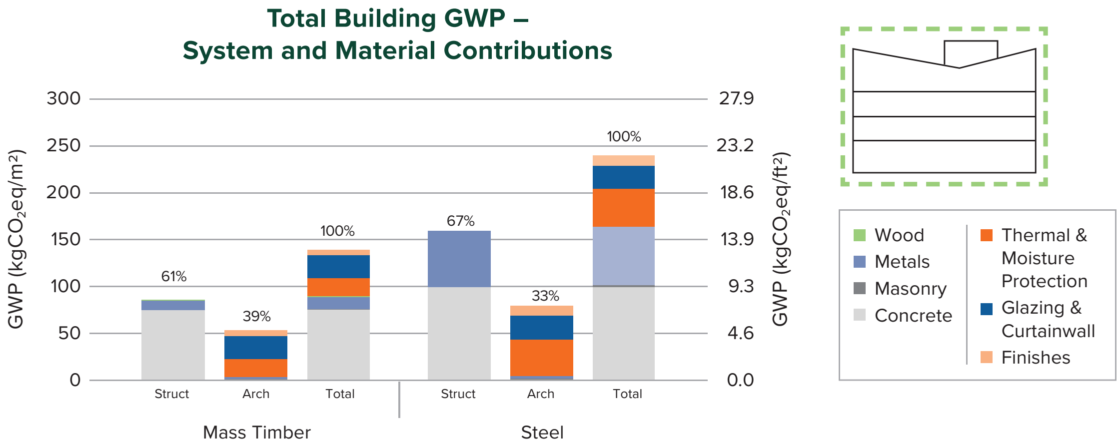


FIGURE 13: Total building GWP comparison of the buildings by structural and architectural components and their material contributions

Figure 13 provides further detail on the total GWP impacts by reporting the contributions of each material category and the breakdown between structural and architectural components for each building. The architectural components contribute 39% of the total building GWP for mass timber and 33% for steel, while the structural components contribute 61% for mass timber and 67% for steel.

The GWP impacts of the architectural components of the mass timber building are 32% lower than in the steel building. The main contributors to this difference are the cementitious fireproofing applied to the steel beams and columns to meet FRR requirements, categorized as thermal and moisture protection, and the increased extents of suspended ceiling assemblies used for acoustic and aesthetic purposes (vs. exposed CLT), categorized as finishes. The cementitious fireproofing contributed 164,143 $kgCO_2eq$ (18 $kgCO_2eq/m^2$) to the steel building's GWP and is not present in the mass timber building. The steel building's ceiling assemblies resulted in an increase of 57,774 $kgCO_2eq$ (6.3 $kgCO_2eq/m^2$) compared to the mass timber building.

Isolating the structural components, the mass timber building has 46% less GWP than the steel building. The concrete material is a significant contributor to the GWP impact of both buildings because concrete has a high GWP intensity, and they both contain large amounts of concrete. Concrete contributes roughly 54% of the total mass timber building GWP and 63% of the mass, and 42% of the total steel building GWP and 80% of the mass. The precast concrete cores make up 13% of the total concrete volume in the mass timber building and 15% in the steel building. They contribute 90,813 $kgCO_2eq$ (10 $kgCO_2eq/m^2$) to the mass timber building's GWP and 158,370 $kgCO_2eq$ (17 $kgCO_2eq/m^2$) to the steel building's GWP, illustrating that the use of a CLT panel core instead of a precast concrete core can result in a meaningful reduction to the overall GWP.

Because concrete makes a sizeable contribution to the building material volumes and GWP impacts, it is helpful to separate the substructure, which contains large amounts of concrete, from the superstructure to better understand how the mass timber and conventional steel systems compare. "Superstructure" refers to all elements except foundations and slab-on-grade (Figure 14). "Substructure" refers to the foundation and slab-on-grade system, including isolated footings, spread footings, mat foundations, stem walls, and concrete pedestals. Superstructure and substructure results are presented in terms of GWP per total building gross floor area. "Total building" refers to all elements in both the substructure and superstructure.

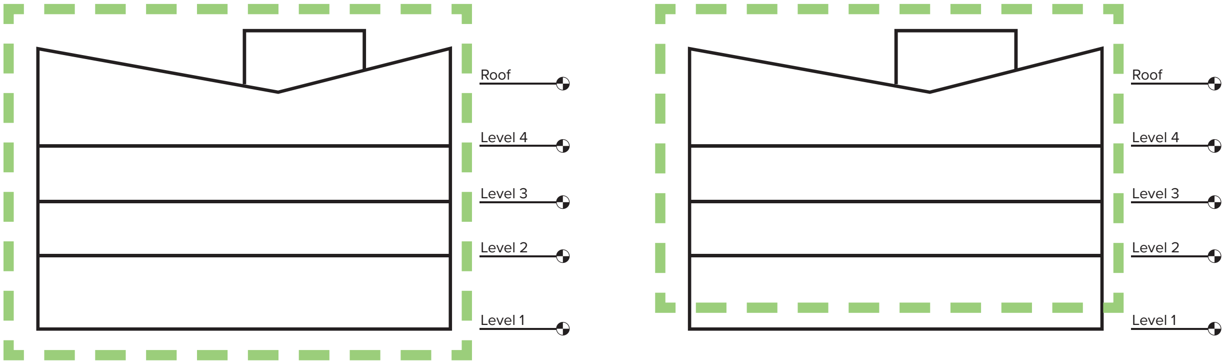


FIGURE 14: Schematic sections defining the meaning of "total building" (substructure and superstructure) (left) and "superstructure" (right)

Figure 15 illustrates the superstructure's total (structure and architecture) GWP impact of the two systems and Figure 16 isolates the superstructure's structural GWP impact of the two systems. The superstructure's total GWP impact is 870,360 kgCO$_2$eq (95 kgCO$_2$eq/m^2) for the mass timber system and 1,756,465 kgCO$_2$eq (192 kgCO$_2$eq/m^2) for the steel system. The superstructure's structural GWP impact is 377,474 kgCO$_2$eq (41 kgCO$_2$eq/m^2) for the mass timber system and 1,028,997 kgCO$_2$eq (113 kgCO$_2$eq/m^2) for the steel system.

The mass timber superstructure system has 50% less GWP than the steel system when both structural and architectural components are considered, and 63% less GWP when considering only structural components. The GWP savings recognized by the structural superstructure system of the mass timber building is equivalent to 155 gas-powered passenger vehicles driven for one year or the electricity needed to power 85 homes for one year (United States Environmental Protection Agency, 2024).

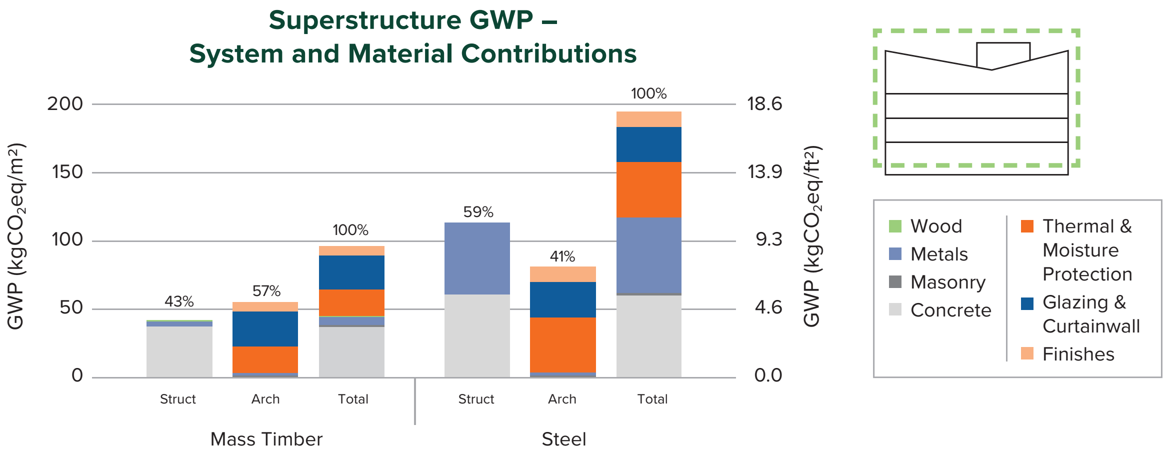


FIGURE 15: Superstructure GWP comparison of the systems by structural and architectural components and their material contributions

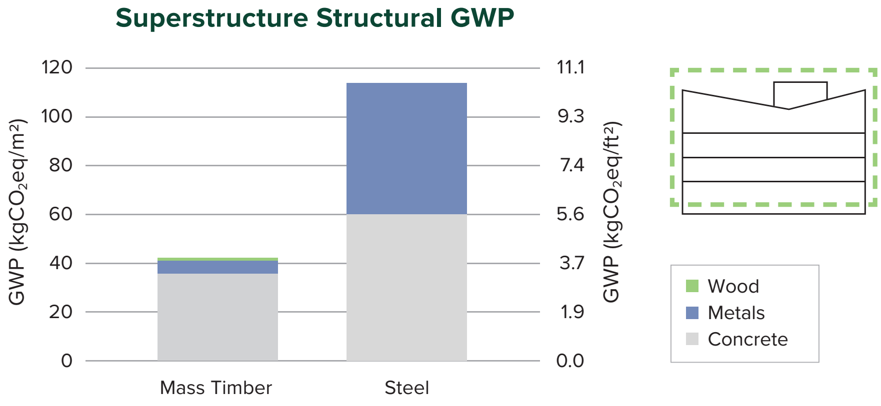


FIGURE 16: Superstructure structural GWP comparison of the two systems and material contributions

Figure 17 shows the relative percentages of the superstructure's structural material mass compared to its relative GWP contribution for both systems. In the mass timber system, the mass is comprised of 54% concrete material, 45% mass timber, and just 1% steel (primarily steel reinforcement). Concrete dominates the superstructure GWP impact of the mass timber system, contributing 88% of the GWP. The concrete elements of the superstructure are the 3-in. topping slabs on CLT panels, two precast concrete cores, and 8-in. rainwater retaining walls at the roof. The mass timber material contributes roughly 0.5% to the superstructure GWP and the steel material about 10%.

In the steel building, concrete dominates the superstructure's mass at 85%, a 33% increase in volume compared to the mass timber system, and contributes 53% of the GWP impact. Concrete elements include floor slabs on metal deck, three precast concrete cores, and 8-in. rainwater retaining walls at the roof. Steel contributes 15% to the superstructure mass and about 47% of the GWP, highlighting the high GWP intensity of steel materials.

Figure 18 shows the GWP impact of the architectural components, separated into four use categories: vertical enclosure, horizontal enclosure, interior assemblies, and ceilings. As noted, the architectural GWP of the mass timber building is 32% less than the steel building, primarily due to the fireproofing materials and additional ceilings required in the steel building.

The GWP impact of the interior assemblies in the mass timber system is 89% less than that of the steel building. This is attributed to the inherent fire resistance of mass timber, considering a char layer, vs. the addition of spray-applied cementitious fireproofing material on the steel beams and columns to achieve the required FRR. The GWP impact of the ceilings in the mass timber system is 67% less than that of the steel building, simply because there is 49,220 ft² less dropped ceiling locations. The GWP impact of the vertical enclosure in the mass timber system is 5% less because the total building height is 2 ft shorter than the steel building. The GWP impact of the horizontal enclosure is the same for the two buildings because the architectural components of the roof assemblies are identical.

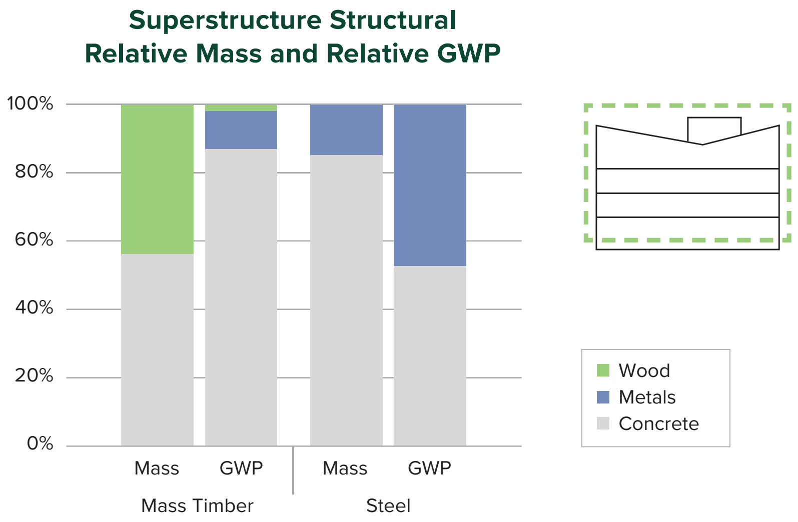


FIGURE 17: Superstructure structural GWP comparison of the systems and material contributions

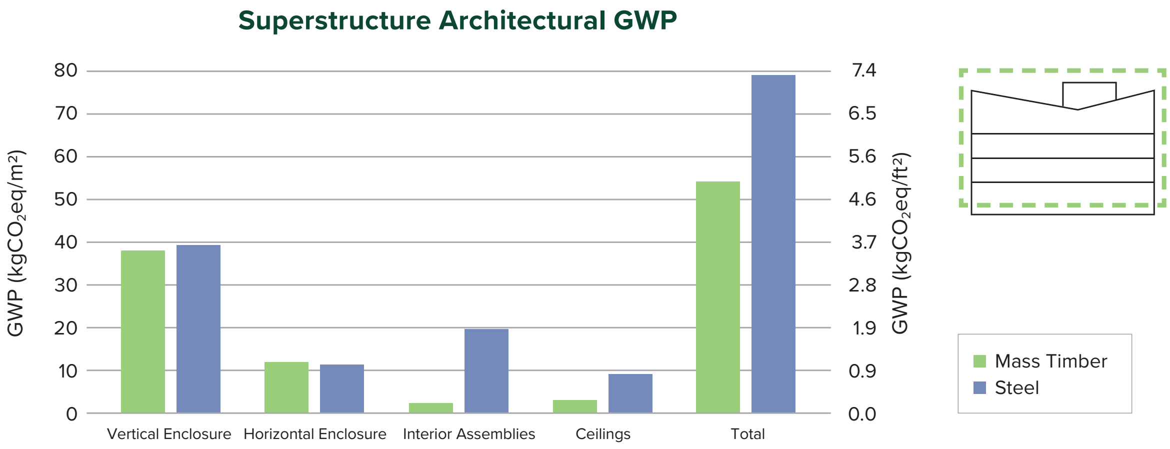


FIGURE 18: Superstructure architectural GWP comparison of the systems by use category

Figure 19 illustrates the percent contributions of the superstructure’s architectural and structural GWP impacts of the two systems. The architectural components contribute more than half the GWP impact of the mass timber system, but less than half in the steel system. Even though the mass timber building has a higher percentage of architectural GWP impact, the structural system's GWP is 63% less than the steel system and the total architectural impacts in the mass timber building are less than those for the steel building.

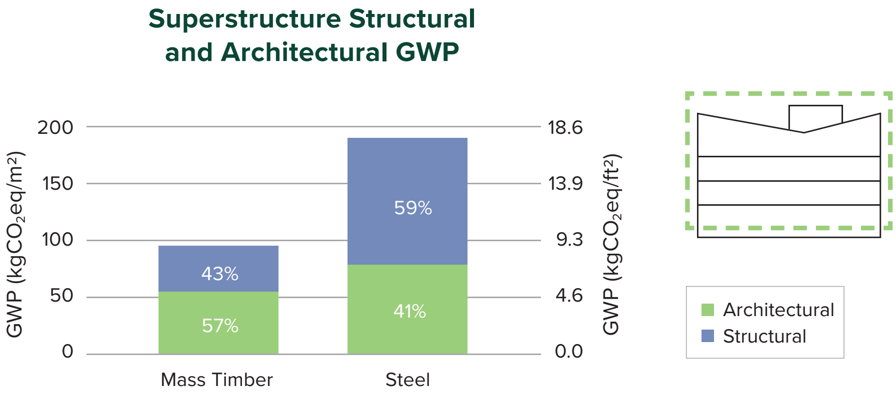


FIGURE 19: Superstructure relative structural and architectural GWP of the two systems

Figure 20 summarizes the contribution of the substructure and superstructure's structural components in both buildings. The substructure (foundation and slab-on-grade) GWP impacts are similar for the two buildings. The steel building's substructure has 6% more concrete volume than the mass timber building, resulting in a 6% higher GWP impact. This difference is due to the thickened continuous and isolated footings and increased area and thickness of the mat slab foundations. In the mass timber system, the substructure contributes 52% (404,761 kgCO_2eq) of the structural GWP impact, while the superstructure contributes 48% (377,474 kgCO_2eq). In the steel system, the substructure contributes 29% (429,337 kgCO_2eq) while the superstructure contributes the majority of the structural GWP at 71% (1,028,997 kgCO_2eq). The slab-on-grade contributes 146,087 kgCO_2eq to both buildings' substructure.

Figure 21 illustrates the life cycle stage contributions to the total building GWP. The dominant stages differ for each building, with the Production Stage (A1-A3) dominating the steel building and the End-of-Life Stage, Stage C, dominating the mass timber building. Biogenic carbon contained in the mass timber material enters the system as a negative impact in the Production Stage (A1-A3), resulting in a net negative impact (-81 kgCO_2eq/m^2) because the biogenic carbon entering the system offsets all the GWP fossil emissions.

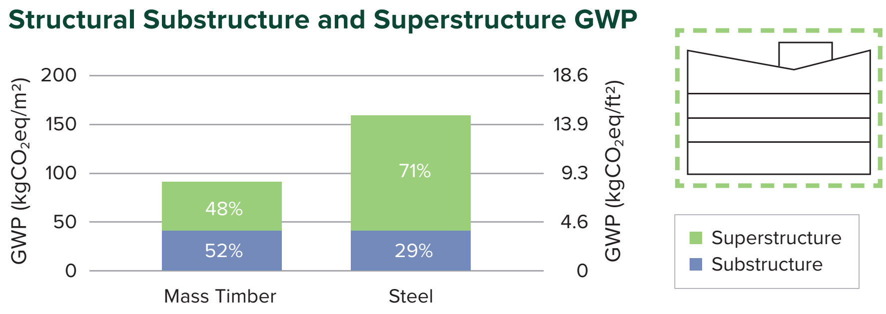


FIGURE 20: Structural substructure and superstructure relative contributions to total structural GWP of the two buildings

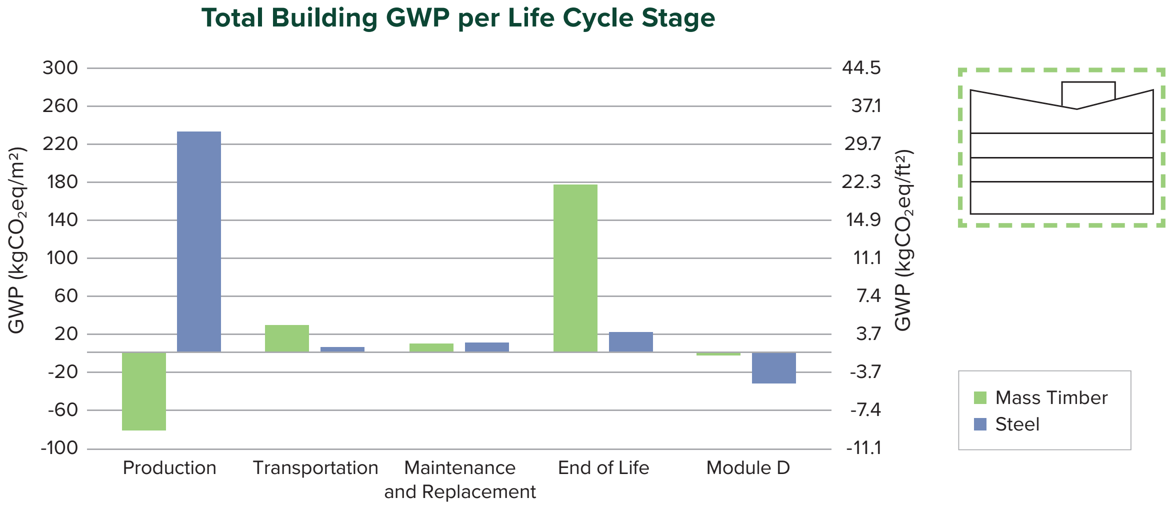


FIGURE 21: Total building GWP per life cycle stage comparison of the buildings

Transportation (A4) has a negligible impact in the steel building and contributes 20% of the total impact of the mass timber building. For all materials except mass timber, the transportation distance and type are set to TallyLCA defaults based on U.S. averages specific to the material. The A4 impact of the mass timber material was modified to consider the distance from the assumed supplier in Chibougamau, Quebec, Canada, to Denver, Colorado, totaling 2,450 miles (3,940 km). Even with this long distance, the total A4 impact of the mass timber building is equivalent to 35% of the stored biogenic carbon within the mass timber material, highlighting the importance of material choice over transportation distances to minimize a building's embodied carbon impact.

The Maintenance, Repair, Replacement and Refurbishment modules (B2-B5) have a minimal impact as only roof finishes and windows are assumed to be replaced at 40 years, before the end of the building's service life. All other materials are set to the lifespan of the building.

The End-of-Life Stage (C2-C4) has the highest impact in the mass timber building due to the release of stored biogenic carbon. The LCA assumes 31.75% of the biogenic carbon is permanently stored. Reference the series introduction for a description of TallyLCA's end-of-life assumptions and mix allocation.

Module D is considered outside of a building's system boundary (A-C) and its benefits and burdens ultimately belong to the next system, such as another building or physical product. TallyLCA does not allow the proper exclusion or separation of benefits and impacts that occur beyond the system boundary from the analysis. Therefore, as discussed in the series introduction, Module D is included for all materials in this report.

Module D has a net negative impact for both buildings, primarily due to the recyclability of architectural and structural metals, crediting the system for recycling their respective portions of net scrap. For the steel building, these materials include steel reinforcing, HSS, wide-flange steel, metal deck, CFS metal studs, curtain wall mullions, mineral wool insulation, and MCM panel. For the mass timber building, steel materials include steel reinforcing, curtain wall mullions, MCM panel, and mineral wool insulation. The steel building has a higher net negative impact at Module D because it has a higher content of metal materials compared to the mass timber building. The mass timber material alone has a net positive impact in Module D. However, the negative impact of the metal components offsets these positive impacts, resulting in an overall net negative impact for Module D in the mass timber building.

Figure 22 illustrates the life cycle stage percentage contribution of the major materials within this study. Stage A1-A3 dominates the GWP contribution of all materials. Materials that have a replacement period in Stage B have nearly equal impacts in Stages A1-A3 and B.

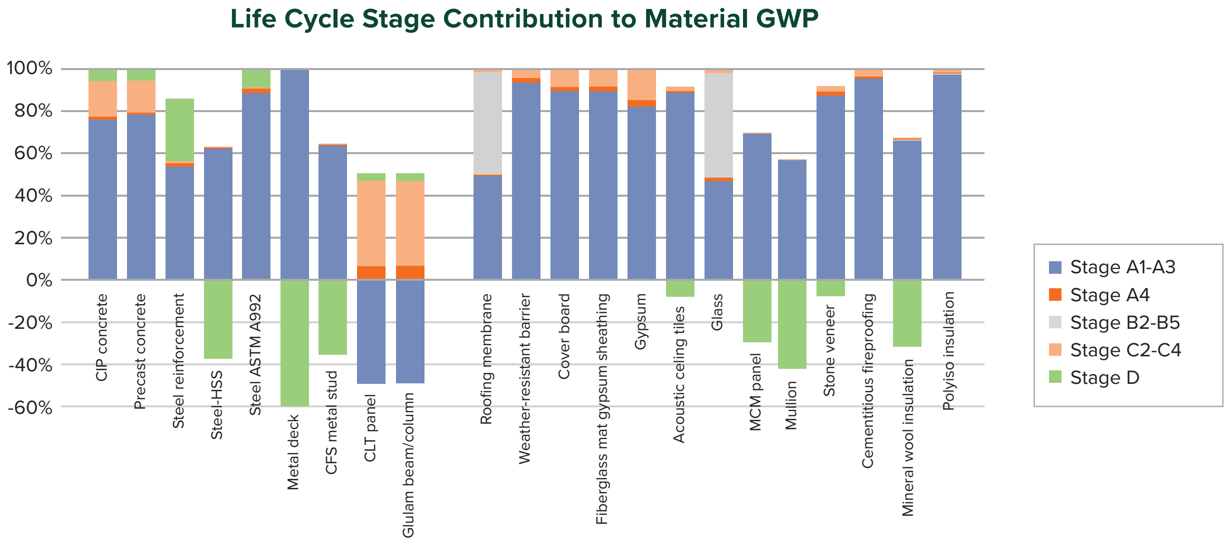


FIGURE 22: Life cycle stage GWP contributions per material

As noted in Figure 21, both buildings receive a benefit with the inclusion of Module D due to their use of steel elements and the assumption that 98% of steel material is recycled and net scrap is credited as avoided burden. This means that the more virgin material used to manufacture the product (Stage A1-A3), the greater the benefits (credits) to the material in Module D, as is the case for HSS, metal deck, CFS studs, MCM panels, curtain wall mullions, and mineral wool insulation (Figure 22). If the percentage of recycled content in the product exceeds the percent allocated to recycling at end-of-life, the product will have a net burden in Module D, which is the case for wide-flange steel (ASTM A992) and steel reinforcement.

Although TallyLCA assigns Module D benefits based on the assumption that most of the steel material will be recycled, metal deck and reinforcing bars present a challenge for end-of-life recovery and recycling because they are interlocked with concrete material. Additionally, to recycle the steel beams and columns, the cementitious fireproofing material would need to be removed.

An important consideration for mass timber material and its potential embodied carbon advantages is the products' end-of-life disposition. The LCA results in this study are based on the end-of-life mix allocation assumptions used in TallyLCA, which presume that the majority of the biogenic carbon is released back into the atmosphere via incineration or decomposition at landfill, while 31.75% is permanently stored (Feitel & Kingsley, 2024).

To illustrate the biogenic carbon content of the mass timber system, Figure 23 shows the stored biogenic carbon of each mass timber component type per total building gross floor area (at Stage A). The best-case scenario at a building's end-of-life is that the mass timber material stores all the biogenic carbon content indefinitely, through deconstruction, recovery, and direct reuse, or the building service life reaches 100 years, at which point the biogenic carbon is considered to be permanently stored (Biotechnology Industry Organization, n.d.). The combined stored biogenic carbon of the CLT and glulam elements is significant, roughly -256 kgCO_2eq/m^2. The contribution of CLT to the stored biogenic carbon is 65% (-167 kgCO_2eq/m^2).

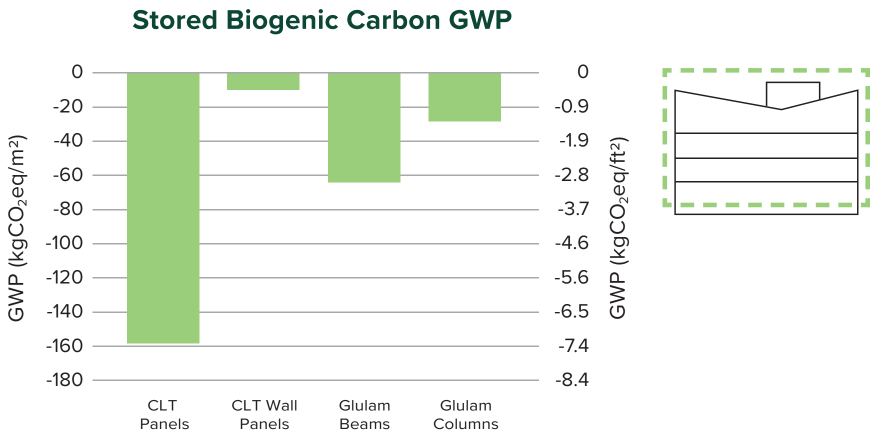


FIGURE 23: Stored biogenic carbon GWP of the mass timber building

GWP is the impact category discussed primarily in this study as it represents all greenhouse gas (GHG) emissions in proportion to their relative influence in creating the conditions for global temperature rise. GHG emissions impacts “can be reported with clarity, as they have a high degree of global agreement on reporting methods [...] The emissions of GHGs anywhere in the world results in the same global impact on climate change” (Simonen, 2014).

Alternatively, effects and risks of other environmental impacts are locally and regionally dependent. Table 4 shows all impact categories calculated in the LCAs, normalized to the mass timber building LCA results. Results of this study show that the mass timber building has a lower impact in GWP and non-renewable energy demand, but the steel building has a lower impact in the other categories.

Environmental Impact Categories					
Impact Category	**Unit**	**Mass Timber**		**Steel**	
Acidification Potential	$kgSO_2eq/m^2$	1.72E+00	100%	1.05E+00	61%
Eutrophication Potential	$kgNeq/m^2$	2.32E-01	100%	4.89E-02	21%
Global Warming Potential	$kgCO_2eq/m^2$	1.40E+02	100%	2.39E+02	171%
Ozone Depletion Potential	$CFC\text{-}11eq/m^2$	9.69E-06	100%	2.07E-06	21%
Smog Formation Potential	kgO_3eq/m^2	2.06E+01	100%	1.40E+01	68%
Primary Energy Demand	MJ/m^2	4.12E+03	100%	2.91E+03	71%
Nonrenewable Energy Demand	MJ/m^2	2.60E+03	100%	2.77E+03	106%
Renewable Energy Demand	MJ/m^2	1.51E+03	100%	1.46E+02	10%

TABLE 4: Total Stages A-C plus Module D environmental impact category results for both buildings

Supplemental Life Cycle Assessment Results

As discussed in the series introduction, the results of the LCAs are dependent on the data available within the TallyLCA database and its methodology at the time of the analysis. The purpose of this section is to compare some of the data used in TallyLCA with currently available industry information and discuss the potential effects on the comparative LCA results.

Glued-Laminated Timber (Glulam)

Glulam data within TallyLCA is based on the American Wood Council and Canadian Wood Council's (AWC/CWC's) 2013 *Industry-Average EPD for Glued-Laminated Timbers*, which expired in 2019 and was selected to represent all glulam within the mass timber building LCA as described in the series introduction. The current North American industry average EPD, issued in 2020, was not available within TallyLCA at the time of this analysis.[7]

The glulam manufacturer selected for this building is Nordic Structures. Their 2023 *Environmental Product Declaration Nordic Lam* has roughly a 31% (62 $kgCO_2eq/m^3$) lower A1-A3 GWP impact than the default values used in TallyLCA. If the LCA's A1-A3 GWP data is replaced with the Nordic Structures EPD data, the GWP impact of the glulam beams and columns would decrease by 51,672 $kgCO_2eq$ (6 $kgCO_2eq/m^2$) in the mass timber building. This would result in a 7% reduction of the structural A-D GWP and a 4% reduction of the total building A-D GWP.

Cross-Laminated Timber (CLT)

The TallyLCA database does not include any North American manufacturer-specific EPDs, though many are publicly available. It does, however, offer an LCI data set based on the AWC/CWC's outdated 2013 EPD mentioned above. TallyLCA uses a proxied method to ratio glulam impacts and biogenic carbon content to the density of a typical CLT product, as described in the series introduction.

Nordic Structures is also selected to manufacture the CLT for this building. Their 2023 *Environmental Product Declaration Nordic X-Lam* has roughly a 62% (112 $kgCO_2eq/m^3$) lower A1-A3 impact than the CLT data used in TallyLCA. If the LCA's A1-A3 GWP data is replaced with the current Nordic Structures' EPD data, the GWP impact of the CLT floors, roofs, and walls would decrease by 191,925 $kgCO_2eq$ (21 $kgCO_2eq/m^2$) in the mass timber building. This would result in an 25% reduction of the structural A-D GWP and a 15% reduction of the total building A-D GWP. This is a significant reduction due to the large amount of CLT relative to glulam throughout the building (51% more CLT than glulam by volume).

If Nordic Structures' EPD data is used for both the glulam and CLT, the mass timber building's total GWP decreases from 42% less than the steel building to 53% less.

Concrete Mixes

The concrete industry has many strategies to reduce the embodied carbon intensity of its products (GWP impact per volume). The strategy employed for the LCAs compared in this study is to replace cement with SCMs, specifically fly ash, as discussed in the section, Concrete Mix Designs. This is a standard approach in the Denver market. Lower embodied carbon-intensive mix designs would reduce the GWP impact of both building systems.

If TallyLCA referenced the NRMCA's 2022 *Concrete Industry-Average EPD* instead of its 2019 predecessor, the effects on the total GWP would be a 6% reduction for the mass timber building and a 4% reduction for the steel building. See the series introduction for more information regarding concrete data within TallyLCA.

If Type IL cement, which is now common in the Denver market, is used instead of Type I/II cement, the total GWP would decrease by 5% for the mass timber building and 4% for the steel building.

The compounding GWP reduction considering the 2022 NRMCA EPD and Type IL cement is 11% for the mass timber building and 8% for the steel building.

Cost and Speed of Construction Results

This building study focuses primarily on WBLCA and embodied carbon impact implications of design choices. Building material and system selections also have cost impacts in terms of dollars and time. This section endeavors to answer the question: *What is the dollar cost of lower embodied carbon systems and material choices?*

This cost study is based on the reference mass timber office building's DD documents and initial guaranteed maximum price (GMP). PCL Construction prepared an additional estimate for the steel alternate described in this report. All costs are normalized to the March 2024 cost of materials and labor.

The comparative analysis performed for this study includes all substructure, superstructure, and architectural and structural components as described in the previous sections, plus all other building components, such as site work, MEP, and interior finish components.[8] The exterior vertical enclosure was important to capture in the cost analysis due to the variation in floor-to-floor and total building heights. The fire-rated assemblies and requirements were also important to capture as their design, installation, and material volumes vary across the two building systems. Special systems used to install the structure and protect it from the elements during construction, such as concrete formwork, mass timber ultraviolet light and moisture protection, were included in the estimates.

It is typical for the initial pricing of mass timber systems to show a dollar cost premium over conventional systems, and this building was no different. Considering structural raw material for the total building, the premium is a striking 126% for the mass timber system compared to the steel system. These relative cost comparisons and premiums are illustrated in Figure 24. This premium is primarily due to the cost difference between the mass timber and steel material. The mass timber material cost exceeds $70/square foot, while the steel material cost is less than $35/square foot.

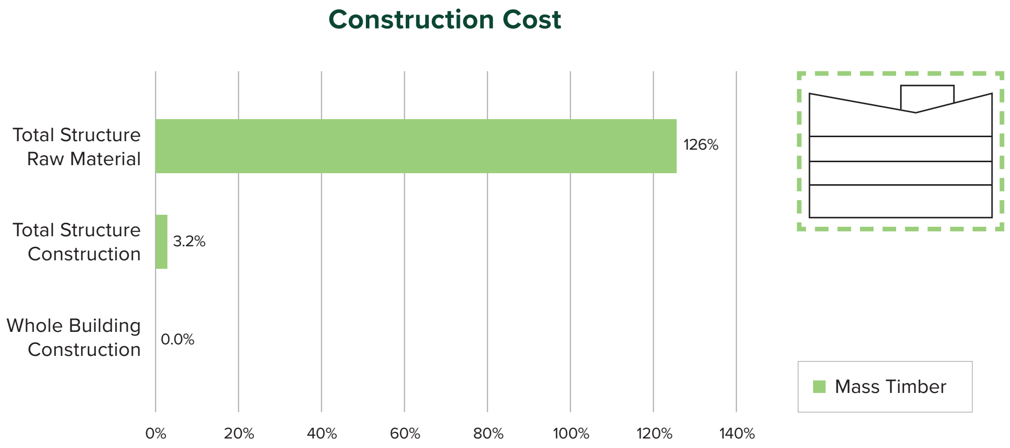


FIGURE 24: Construction cost premiums of both building systems, relative to the steel building cost (illustrates progression of the cost analysis)

Larger and multi-story buildings can often be constructed in less time with a mass timber system than with steel. For Denver Office, PCL estimated that the mass timber building could be built in 16 months and the steel building in 18.5 months. This means the mass timber building could be completed 2.5 months faster (14% faster) than steel. The dollar cost analysis took this into account by considering general conditions (labor), general requirements (equipment and waste), crane costs, urban site logistics, and the substantial variations in finishes such as topping slabs, fireproofing, and ceilings, and is termed “total structure construction.” With these compounding considerations, the cost premium for the mass timber system reduces significantly from 126% to 3.2%. Isolating the dollar costs of logistics and schedule (no hard material costs), the mass timber system is less expensive; the steel system has a 21% premium.

A small cost premium may be acceptable because of mass timber’s ability to reduce the building’s embodied carbon impact by 42%, speed of construction, market differentiation, and biophilic attributes. However, when considering the whole building construction cost,[9] the mass timber building is cost neutral when compared to the steel building. Developer liability insurance premiums, any financial benefits or losses to the developer associated with the time-value of money, such as interest premiums, financial benefits or losses to the developer associated with the lease or sale market value of the building, and potential carbon credits or carbon taxes are excluded from the cost analysis.

The authors of this building study speculate that consumer demand for sustainable buildings and biophilic aesthetics will increase over time, leading building developers and owners to consider, measure, and report the sustainability of their building products.

Conclusion

This building study endeavors to answer the questions: *How does mass timber compare to traditional structural systems? Is mass timber more sustainable? What are the associated dollar cost premiums?*

The LCA and dollar cost results presented in this study illustrate that a mass timber system, for a building of this construction type and occupancy, can have significant embodied carbon savings for no dollar cost premium and realize construction schedule benefits when compared to a functionally equivalent steel structural system.

Specifically:

- Considering the buildings' total GWP impact, the mass timber system GWP is 42% less than the steel system.
- Considering only the structure of the superstructure, the mass timber system GWP is 63% less than the steel system.
- Considering all structural and architectural systems of the superstructure, the mass timber system GWP is 50% less than the steel system.
- The mass timber system could be constructed 2.5 months faster (14% faster) than the steel system.
- Material pricing showed a dollar cost premium of 126% for the mass timber system. However, when considering the whole building construction cost, including cost savings associated with the shorter construction duration and variation in fireproofing and finish materials, the mass timber building is cost-neutral to the steel building.

Despite clear material cost premiums, cost-competitive mass timber solutions are achievable with thoughtful design, material optimization, designing for constructability, and thorough, holistic cost estimating that includes the schedule and labor savings as a real component of construction cost.

The building industry has a significant opportunity and responsibility to address climate change and environmental impacts, due to its outsized global emissions impact. This study explores a mass timber structural system as one potential embodied carbon reduction strategy, due to the material's relatively low manufacturing GWP impacts and its natural ability to store biogenic carbon. However, the building design and construction industry will also need to consider bolder, innovative, multifaceted reduction opportunities for all systems—including both design and material strategies. The implementation of mass timber systems should be considered as a viable approach to minimizing a building's embodied carbon impact with the understanding that building life expectancy, material sourcing,[3] and end-of-life pathways[4] also influence cradle-to-grave results.

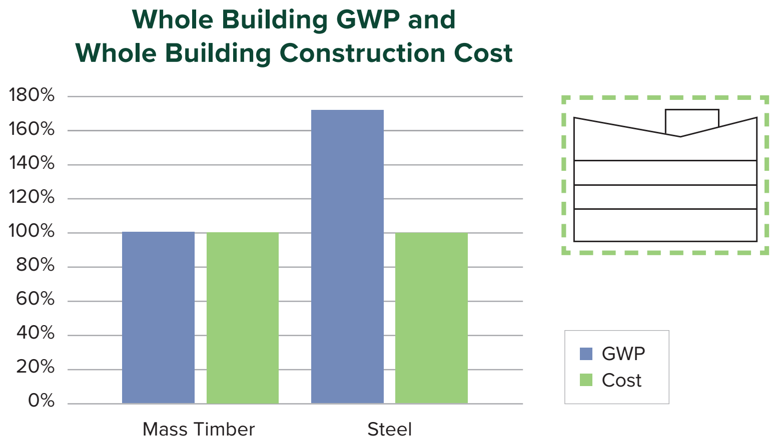


FIGURE 25: Total building GWP (structure and architecture, including the enclosure, fire resistance-rated assemblies, acoustic assemblies, and interior ceiling finishes) and whole building construction cost comparison of the building systems, normalized to the GWP and cost of the mass timber system

End Notes

1. Functionally equivalent means the same design criteria as the reference system: equivalent floor area, site orientation, occupancy, general programmatic layout, geographic location, load criteria, and performance requirements, in accordance with ISO 14044 4.2.3.7 and ASTM E2921.
2. For more information on biogenic carbon, see the *Mass Timber Comparative Life Cycle Assessment Series Introduction* (Feitel & Kingsley, 2024).
3. Wood products sourced from North American forests meet the definition of sustainable sourcing per ISO 21930 Section 7.2.1.1. For more information, see the *Mass Timber Comparative Life Cycle Assessment Series Introduction*.
4. End-of-life considerations are included in the cradle-to-grave LCA results and are based on TallyLCA's end-of-life allocation assumptions, as described in the *Mass Timber Comparative Life Cycle Assessment Series Introduction*.
5. This method of fire resistance is referenced in IBC Section 722.1 and defined in NDS Chapter 16, and is allowed for fire-resistance ratings up to 2 hours. For more information see the WoodWorks paper, *Fire Design of Mass Timber Members*, available at www.woodworks.org.
6. Primary concrete reinforcing steel is included, such as typical reinforcement in slabs, walls, and footings, and vertical bars and ties in pilasters. Secondary reinforcing steel such as lap splices, dowels, connections, drag bars, and corner detailing are excluded.
7. Prior to the publication of this building study, but after the LCAs were performed, TallyLCA added the AWC/CWC 2020 *Industry-Average EPD for Glued-Laminated Timbers* to its database.
8. The reported construction costs do not include the costs associated with the lower embodied carbon concrete mix designs described in the section Concrete Mix Designs.
9. Whole building construction cost includes the material and installation of the foundation substructure, floor and roof superstructure, all architectural, mechanical, electrical, plumbing, and civil costs, as well as schedule-related costs like general conditions, labor, equipment, waste, and site logistics. As noted in the series introduction, costs such as developer liability insurance premiums, and financial gains or losses to the developer associated with time-value of money or any market value sale of the building are not included.

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Appendix

TallyLCA® Data Selection[1]	Total Mass (kg)	
	Mass Timber	Steel
Acoustic ceiling tile (ACT), mineral fiber board	5,667.29	5,792.81
Adhesive, acrylic	1,763.08	881.54
Aluminum curtain wall system, YKK AP - EPD	5,218.67	5,432.96
Aluminum extrusion, AEC - EPD	2,943.63	3,614.51
Aluminum storefront system, YKK AP - EPD	4,708.21	4,708.21
Aluminum-faced composite wall panel (ACM), MCA - EPD	11,434.09	15,221.94
CLT (Cross laminated timber)	841,025.33	0.00
Cold formed structural steel	14,393.46	15,827.07
Concrete masonry unit (CMU), hollow-core	28,559.16	28,559.16
Contruction steel, light structural shapes, CMC - EPD	0.00	16,796.92
Fasteners, galvanized steel	9.18	9.18
Fiberglass mat gypsum sheathing board	49,880.83	54,413.82
Fireproofing, cementitious	0.00	140,746.12
Fluid applied elastomeric air barrier	6,106.94	7,028.70
Glass wool unfaced batt, Knauf, EcoBatt - EPD	3,540.17	6,935.56
Glazing, double, insulated (air)	106,893.62	108,255.87
Hardware, stainless steel	254.09	259.23
Hot rolled structural steel, AISC - EPD	4,000.99	263,423.44
Lightweight concrete, 4000 psi, 0% fly ash and slag	14,616.00	14,616.00
Mortar type S	1,950.47	1,950.47
PIR rigid foam insulation, roof, R=10.2, PIMA - EPD	322.29	894.47
PIR rigid foam insulation, roof, R=20.5, PIMA - EPD	18,295.18	18,544.86
PIR rigid foam insulation, wall, R=14.6, PIMA - EPD	2,662.76	2,928.88
Polyethelene sheet vapor barrier (HDPE)	742.86	720.65
Spandrel, glass, insulated (1 core)	32,997.42	34,432.94
Steel tube, Bull Moose Tube - EPD	0.00	45,191.44
Steel, concrete reinforcing steel, CMC - EPD	61,239.68	66,446.65
Steel, sheet	1,476.77	1,476.77
Stone slab, granite	10,514.03	10,726.53
Structural concrete, 4000 psi, 20% fly ash	1,745,801.33	2,417,244.58
Structural concrete, 5000 psi, 20% fly ash	64,745.29	24,077.57
Structural concrete, 5000 psi, 40% fly ash	912,731.70	1,046,479.16
Structural concrete, 6000 psi, 40% fly ash	397,580.33	693,342.77
Suspended grid	2,409.42	13,794.62
Thickset mortar	30,838.97	30,838.97
TPO membrane, 60 mils, SPRI - EPD	8,157.52	8,157.52
Wall board, gypsum, fire-resistant (Type X)	84,584.79	88,994.93
Wall board, gypsum, natural	13,663.66	71,230.63

1. The TallyLCA® Data Selection name reported is the TallyLCA® formal data entry terminology and represents the LCI and EPD data set for a given product type and specification

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