Mass Timber Comparative Life Cycle Assessment Series

Trends and Conclusions

Author: KL&A Engineers & Builders




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Executive Summary

Mass timber buildings demonstrate meaningful embodied carbon reductions while maintaining cost competitiveness and accelerating construction schedules.

The *Mass Timber Comparative Life Cycle Assessment Series*, developed by KL&A Team Carbon and WoodWorks, endeavored to explore and answer the questions: *How does mass timber compare to traditional structural systems? Is mass timber sustainable? What are the associated dollar cost premiums?*

The goal of the series is to illustrate the embodied carbon and economic implications of selecting mass timber structural systems through analysis of individual projects. It is intended to support the adoption, implementation, and success of mass timber buildings in North America as one of many embodied carbon reduction strategies.

The series is a compilation of four comparative building studies based on reference mass timber buildings in the U.S. The reference buildings are compared to functionally equivalent concrete and/or steel building systems in terms of embodied carbon, using whole building life cycle assessment (WBLCA), dollar cost, and speed of construction. Each study details the building's background, alternative designs, scope, and analysis results.

This report summarizes the individual study results and trends across the series. Because the series is limited to a few buildings in specific locations, the trends cannot be generalized to all buildings; however, broad conclusions and insights are feasible. The key trends and conclusions are:

- The total global warming potential (GWP) savings of the mass timber reference buildings range from **21% to 43%, and average 32%**, compared to their alternative steel and concrete buildings. GWP is measured in kilograms of carbon dioxide equivalent (kgCO_2eq) based on the floor area of the building. The average GWP savings across the four building studies is **88 kgCO_2eq/m²**.
- When isolating the mass timber and alternative structural systems (i.e., superstructure/above-podium structural systems) for comparison, the GWP savings are even larger, ranging from **63% to 118%**. This highlights the unique opportunity of superstructure system selection to reduce building GWP.
- A comparison of whole building construction costs, considering construction schedule differences, shows a cost premium for the mass timber reference buildings ranging from **0% to 6%, and an average of 2.1%**, when compared to their alternative steel and concrete buildings.
- All four mass timber buildings realized faster construction schedules, with an **average schedule savings of 16%**. This time savings benefits both the dollar cost and embodied carbon impact of construction for the mass timber buildings, though these embodied carbon benefits are not quantified by this study.
- The amount of biogenic carbon stored in the mass timber components during the life of the buildings is significant, ranging from **-256 kgCO_2eq/m² to -165 kgCO_2eq/m²**. The total stored biogenic carbon of all four mass timber buildings is equivalent to offsetting the embodied carbon impact of driving an estimated **1,139 cars for a year or the electricity to power 944 homes for a year** (US EPA, 2024).
- The GWP of the mass timber buildings' substructure/podium-and-below structural systems, which are primarily concrete, ranges from **12% less to 6% more** than the alternative designs due to variations related to the superstructure systems. This is relatively minor compared to the superstructure/above-podium GWP savings.

Overall, mass timber systems show significant GWP reductions, speed of construction benefits, and relatively low construction cost premiums. Figure 1 presents the whole building GWP, whole building construction cost, and whole building schedule comparisons of each building study, normalized to the mass timber reference buildings. The results illustrate that mass timber systems should be considered a viable approach to minimizing a building's embodied carbon impact, with the understanding that building life expectancy, material sourcing,[5] and end-of-life pathways[6] will influence the overall embodied carbon performance.

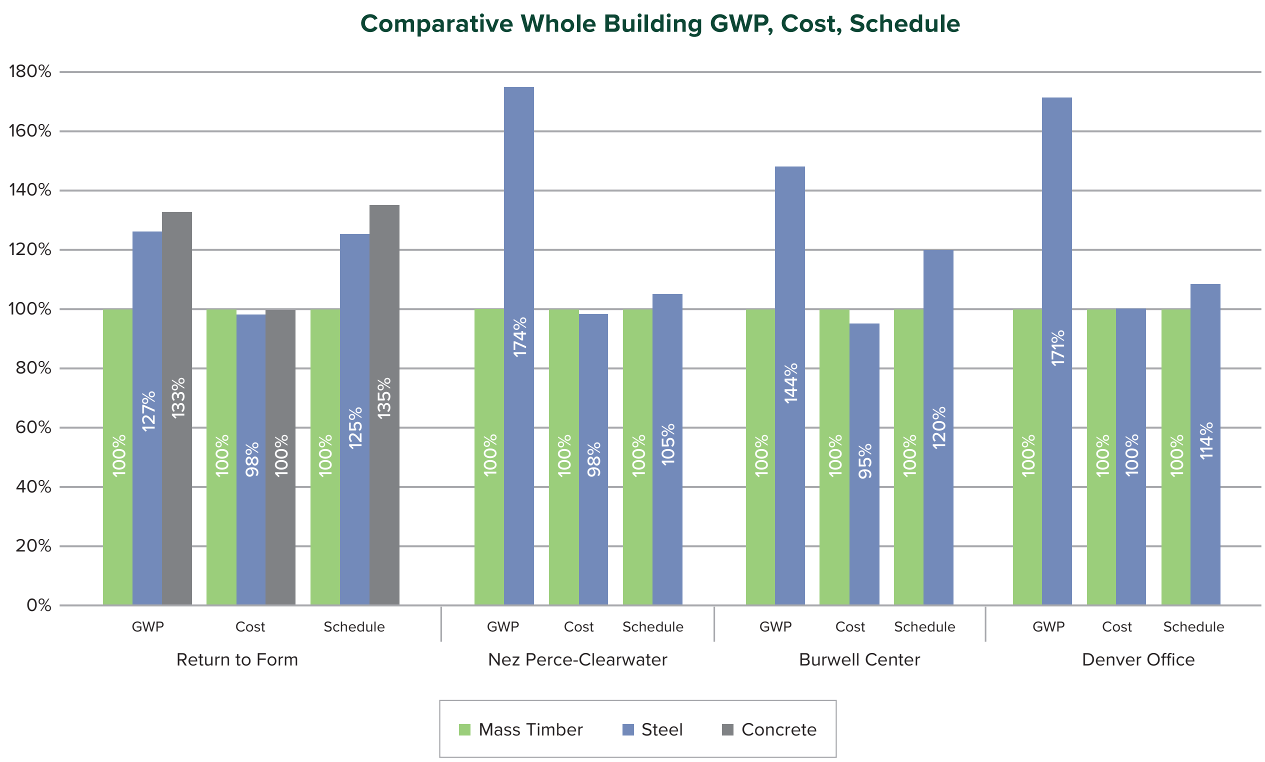


FIGURE 1: Whole building GWP, whole building construction cost, and whole building schedule comparison of the four building studies, normalized to the mass timber reference buildings

Introduction

The *Mass Timber Comparative Life Cycle Assessment Series* consists of four building studies comparing mass timber reference buildings to hypothetical, functionally equivalent[1] steel and concrete alternatives, based on embodied carbon, dollar cost, and construction schedule. The buildings studied are: Return to Form, Nez Perce-Clearwater National Forests Supervisor's Office, Burwell Center for Career Achievement, and Denver Office.

The demand for this series is rooted in the rise in popularity of mass timber structural systems, the lack of embodied carbon data for buildings in the United States, and the increasing importance of sustainable design and construction of buildings. As the building industry moves toward innovations that enable sustainable development, mass timber creates immediate and significant embodied carbon reduction opportunities. However, because building projects also need to be financially viable, cost comparisons were also included in this study.

Building-specific comparisons using whole building life cycle assessment (WBLCA) are the most robust and reliable method of quantifying the embodied carbon savings of mass timber systems. The WBLCAs performed in this series show that, over a range of building sizes, uses, construction types, and framing schemes, mass timber buildings consistently have lower embodied carbon than concrete or steel buildings. Each building study in the series also illustrates mass timber systems' speed of construction benefits and relatively low to zero construction cost premiums, as shown in Figure 1.

This report starts with a brief review of the study methodology followed by a summary of each building study and key results, and then discusses trends across the series. It is intended to be read together with the *Mass Timber Comparative Life Cycle Assessment Series Introduction* (Feitel & Kingsley, 2024) and each building study.

Building Study Methodology

All building studies follow the methodologies, assumptions, and code compliance described in the series introduction. Any deviations are explained within the individual building study reports. Each study compares the original mass timber reference building to one or more alternative buildings using more conventional structural systems and materials and the resulting changes to architectural systems and materials. The alternative building designs are functionally equivalent, meeting the same design criteria as the reference mass timber building, meaning equivalent floor area, site orientation, occupancy, general programmatic layout, geographic location, load criteria, and performance requirements such as fire resistance and acoustics, in accordance with ISO 14044 (ISO, 2006) and ASTM E2921 (ASTM, 2022).

Life Cycle Assessment Methodology and Scope

All life cycle assessments (LCAs) were performed by KL&A Team Carbon using TallyLCA software. The LCA results in this series are limited by the specific environmental product declarations (EPDs) and life cycle inventory (LCI) data available within the TallyLCA database, as well as the end-of-life mix allocation assumptions embedded in the software. The data limitations, uncertainty, and end-of-life allocation are discussed in detail in the series introduction.

The typical component and material scope of the LCAs includes structure, vertical and horizontal enclosures, fire protection assemblies, acoustic assemblies, and interior ceiling finishes; as such, they are considered whole building life cycle assessments. All other architectural finishes (floor finishes, interior wall finishes, paints, furnishings, etc.) are excluded. Site work, civil, landscape, and MEP systems are also excluded. For additional LCA scope inclusions and exclusions, reference the series introduction and individual building study reports.

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 2). The service life of the buildings, representing the reference study period, is 75 years, in compliance with ASTM E2921. The results, discussions, and trends of the series focus on the global warming potential (GWP) impact category, though other impact categories are reported in the individual building study reports. Biogenic carbon flows are included and 31.75% of stored biogenic carbon is assumed to be permanently stored. Concrete carbonation is excluded.

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 2: LCA life cycle stages; scope inclusions in light green

Building System Boundaries

The LCA results within each building study are reported for the total building and separated into systems such as superstructure and substructure, above-podium and podium-and-below, or structural and architectural. This categorization aims to explain the overall GWP outcome of the buildings, identify GWP savings and burdens specific to systems and materials, and identify the trade-offs of design choices.

In this report, the LCA results are presented as “total building” or “superstructure/above-podium.” “Superstructure” refers to the portion of the building above grade, as shown in Figure 3. For Nez Perce-Clearwater, Burwell Center, and Denver Office, the superstructure is either mass timber or an alternative steel system. The term “above-podium” is used only for Return to Form because the building has a concrete podium slab condition at Level 4 and the mass timber or alternative systems comprise the nine stories of residential above Level 4, also indicated in Figure 3.[2] In both cases, the “superstructure” and “above-podium” categories aim to isolate the mass timber portion of the building for a more direct comparison to the alternative structural systems and materials.

Likewise, the “substructure” and “podium-and-below” categories aim to isolate the portions of the structure that are dominated by concrete regardless of the structural system used above. For this reason, three of the four studies (Nez Perce-Clearwater, Burwell Center, and Denver Office) refer to “substructure” as the slab-on-grade and foundation.* For Return to Form, “podium-and-below” refers to the Level 4 concrete podium slab and concrete levels below, including the foundation.

For the trends identified in this report, the “superstructure” systems of Nez Perce-Clearwater, Burwell Center, and Denver Office are categorized with the “above-podium” system of Return to Form. Likewise, the “substructure” systems of Nez Perce-Clearwater, Burwell, and Denver Office are categorized with the “podium-and-below” system of Return to Form.

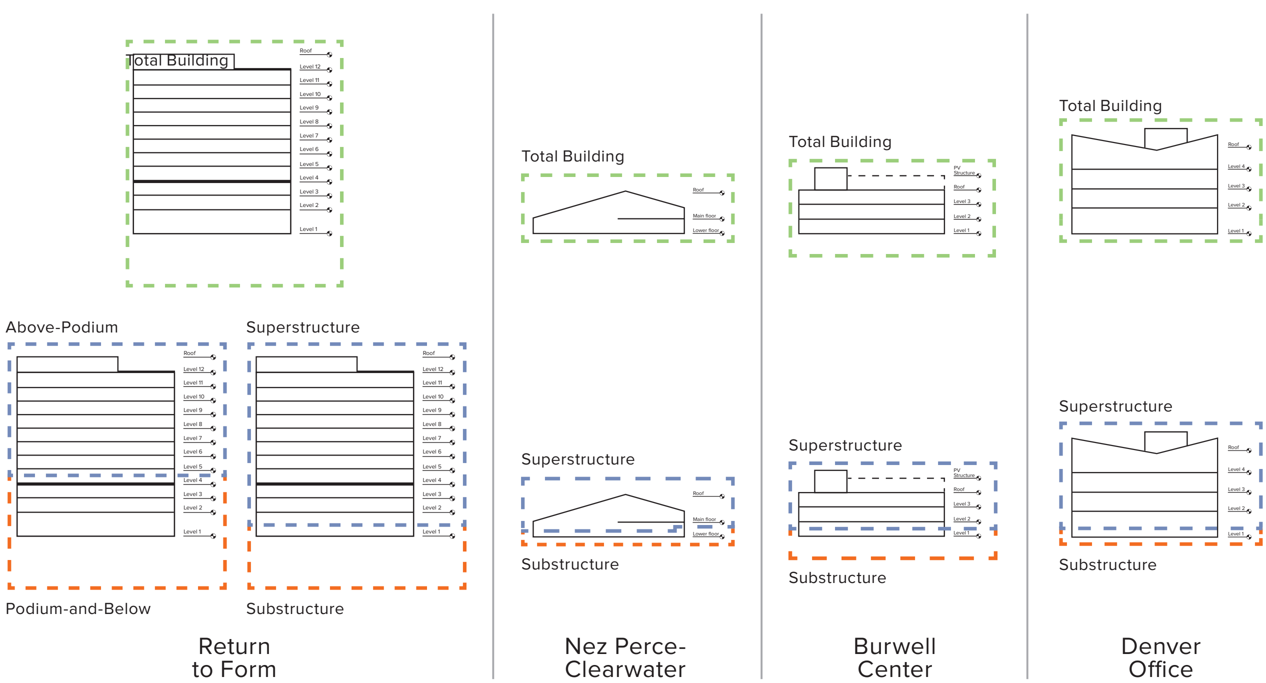


FIGURE 3: Building system boundaries

**Varies from the series introduction*

Dollar Cost and Speed of Construction Methodology and Scope

The dollar cost and speed of construction analyses compare the mass timber buildings' actual construction costs and schedules with those of the alternative designs estimated by either the building's general contractor or other construction professionals. As described in the series introduction, the comparative pricing considers the historic material, labor, and unit prices to match the date of the reference mass timber building data. The analyses include material, installation, labor, site logistics, equipment, and waste. Importantly, construction speed is considered in the dollar cost analyses. In this report, the dollar cost, including all of these components and construction time benefit, is referred to as the whole building construction cost.[3] The analyses, and thus whole building construction cost values, do not account for the developer's liability insurance premiums, any financial benefits or losses to the developer associated with the time-value of money, any financial benefits or losses to the developer associated with the lease or sale market value of the building, nor any potential carbon credits or carbon taxes.

Individual Building Study Descriptions and Results

The following section briefly summarizes each building study, including the construction type, use, location, size, structural system, and analysis results. It also includes illustrations of the schematic building section, 3D images, and typical floor assemblies of each building design.

Of the four reference buildings, three are in Denver, Colorado and one is in Kamiah, Idaho. One is a multifamily building, one is a government office building, and two are higher education office and classroom buildings.

Image: tres birds

Return to Form

Photo: Heidi Long, Longview Studios

Nez Perce-Clearwater

Photo: Frank Ooms

Burwell Center

Image: Shear Adkins Rockmore

Denver Office

Return to Form

The Return to Form study compares three building systems for an 84-unit multi-family residential building: mass timber, cold-formed steel (CFS), and concrete. Although the CFS system is referred to as the “CFS building” within the study, it will be referred to as the “steel building” in this report.

Image: tres birds

Project Details	
Location:	Denver, CO
Date of construction:	Not yet constructed
Date of study:	2023, Construction Documents
Owner:	Katz Development; Wynkoop Investors LLC
Architect:	tres birds
Structural engineer:	KL&A Engineers & Builders
General contractor:	Swinerton
Mass timber supplier	Not yet selected
Building use:	Multi-family residential
Total size:	12 stories / 139,000 ft² (12,900 m²)
Above-podium size:	8 stories / Level 5 to roof / 90,000 ft² (8,350 m²)
Podium and below size:	4 stories / Foundation to Level 4 / 49,000 ft² (4,550m²)

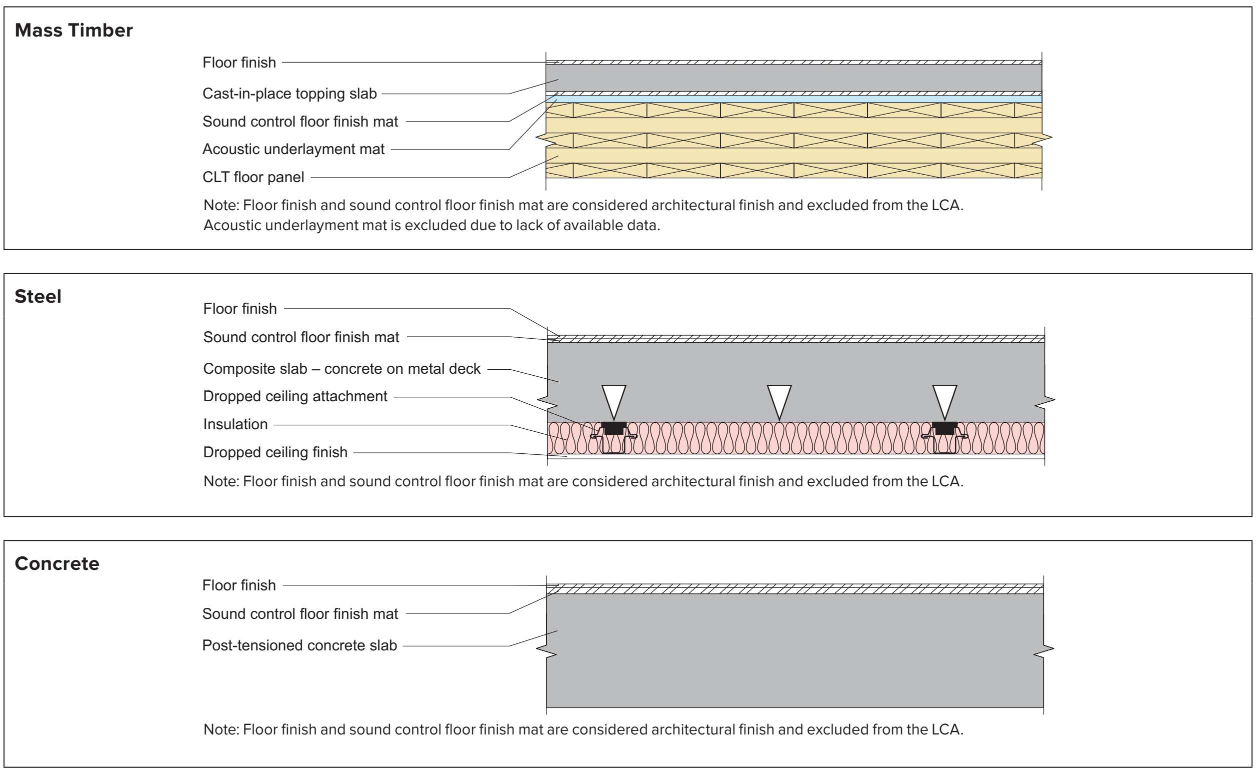
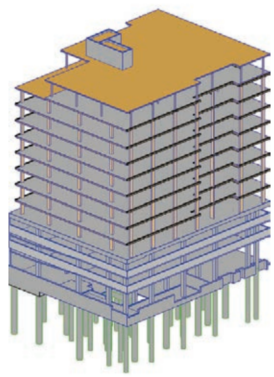
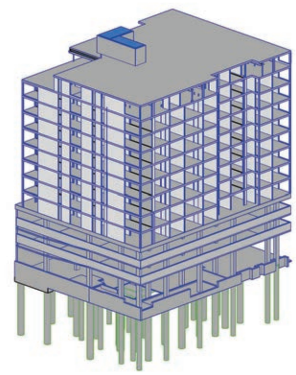
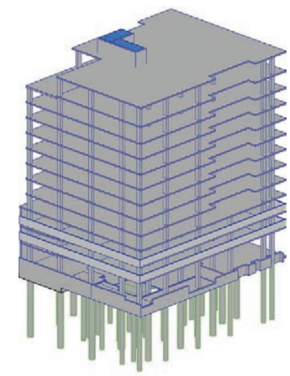


FIGURE 4: Floor assemblies for the Return to Form building system alternatives

TABLE 1: Return to Form summary of design alternatives

		Systems		
				
Program		**Mass Timber**	**Steel**	**Concrete**
Foundations:	–	Concrete drilled piers and grade beams	Concrete drilled piers and grade beams	Concrete drilled piers and grade beams
Level 1:	Mixed use	4-in. concrete slab-on-grade	4-in. concrete slab-on-grade	4-in. concrete slab-on-grade
Levels 2-3:	Parking	8-in. post-tensioned concrete slab	8-in. post-tensioned concrete slab	8-in. post-tensioned concrete slab
Level 4:	Residential	28-in. post-tensioned concrete transfer slab	30-in. post-tensioned concrete transfer slab	8-in. post-tensioned concrete slab
Levels 5-12:	Residential	Post-and-beam framing: Glulam beams and columns, 5-ply CLT, 3-in. concrete topping slab	Bearing wall system: Cold-formed steel stud walls, 5-1/2-in. concrete slab on metal deck	Flat plate system: Concrete columns, 8-in. post-tensioned concrete slab
Roof:	Roof	Post-and-beam framing: Glulam beams and columns, 5-ply CLT	Bearing wall system: Cold-formed steel stud walls, 5-1/2-in. concrete slab on metal deck	Flat plate system: Concrete columns, 8-in. post-tensioned concrete slab
Lateral system:		Concrete core walls	Concrete core walls	Concrete core walls
Volume of structural wood per above-podium area:		0.23 m^3/m^2 (0.76 ft^3/ft^2)	–	–
Exterior wall systems (from exterior to interior):		Finish, insulation, weather barrier, water barrier, gypsum board, non-load-bearing cold-formed steel studs with insulation, gypsum board, interior finish; fully grouted CMU walls at parking		
Construction type:		IV-B	I-B	I-B
Fire rating:		2-hour FRR primary structural frame and bearing walls, 1-hour FRR roof, 0 to 1-hour FRR exterior walls, 0 to 1-hour partition walls		
GWP		**Mass Timber**	**Steel**	**Concrete**
Total building $kgCO_2eq$:		2,616,100	3,310,365	3,485,064
Total building $kgCO_2eq/m^2$ ($kgCO_2eq/ft^2$):		202 (19)	256 (24)	270 (25)
Substructure $kgCO_2eq/m^2$ ($kgCO_2eq/ft^2$):		36 (3)	36 (3)	40 (4)
Superstructure $kgCO_2eq/m^2$ ($kgCO_2eq/ft^2$):		166 (16)	220 (21)	230 (21)
Above-podium per above-podium floor area $kgCO_2eq/m^2$ ($kgCO_2eq/ft^2$):		92 (9)	174 (16)	222 (21)
Podium-and-below plus core walls per gross floor area $kgCO_2eq/m^2$ ($kgCO_2eq/ft^2$):		143 (13)	143 (13)	125 (12)
Construction		**Mass Timber**	**Steel**	**Concrete**
Whole building cost:		+1.8%	Baseline	+1.6%
Speed of construction:		Baseline	+2.0 months (125%)	+4.2 months (135%)

Nez Perce-Clearwater National Forests Supervisor's Office

The Nez Perce-Clearwater study compares two building systems for a government office building: a mass timber/light-frame wood hybrid and steel. Although the hybrid system is referred to as "MT/LF hybrid" in the study, it is referred to as the "mass timber building" in this report.

Project Details	
Location:	Kamiah, ID
Date of construction:	2021
Date of study:	2023, Construction Documents
Owner:	U.S. Forest Service
Architect:	Mosaic Architecture
Structural engineer:	Morrison-Maierle
General contractor:	Quality Contractors, LLC
Mass timber supplier	SmartLam North America
Building use:	Government offices
Total size:	2 stories, 18,540 ft² (1,722 m²)

Photo: Heidi Long, Longview Studios

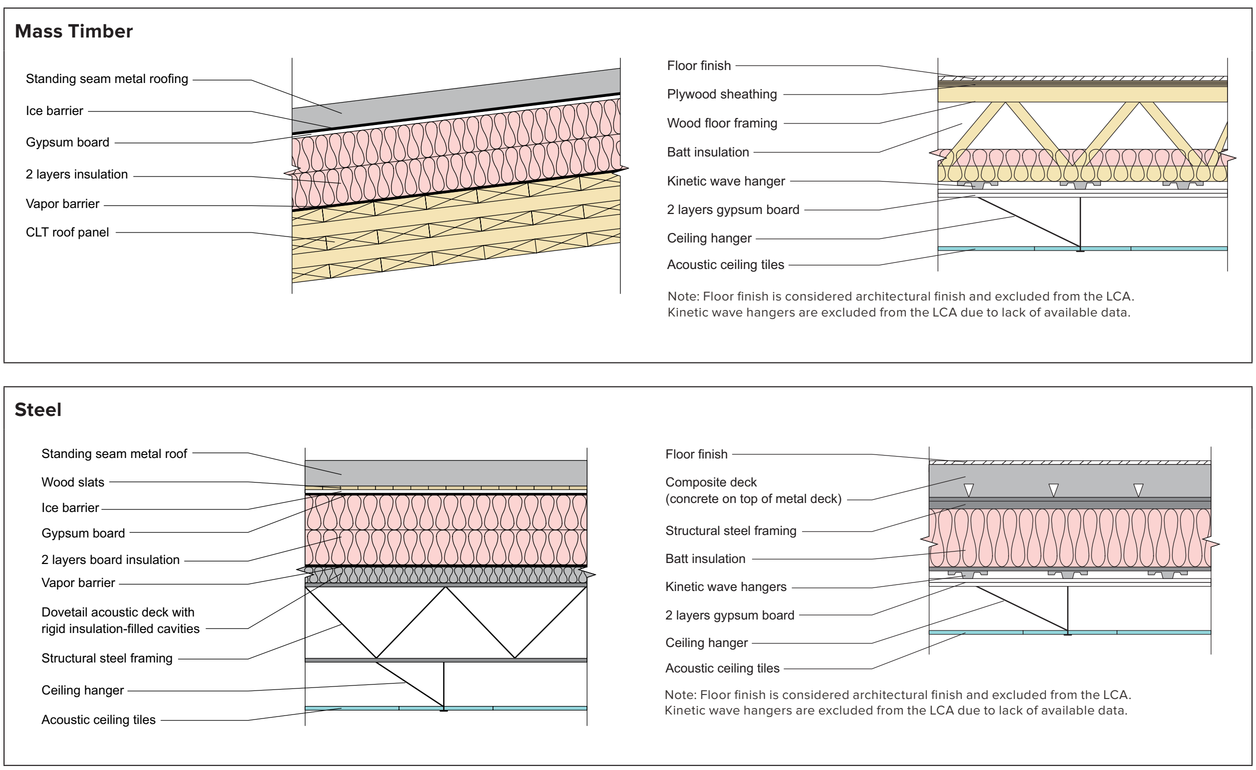
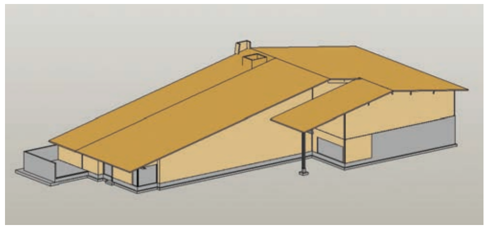
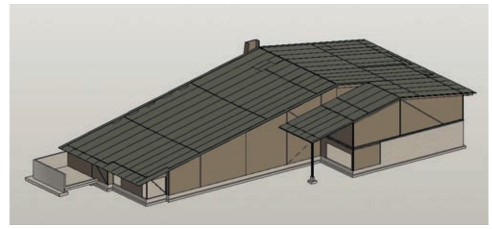


FIGURE 5: Roof assemblies (left) and floor assemblies (right) for the Nez Perce-Clearwater building system alternatives

TABLE 2: Nez Perce-Clearwater summary of design alternatives

		Systems	
			
Program		**Mass Timber**	**Steel**
Foundations:	–	Concrete spread footings, full and partial height foundation walls	Concrete spread footings, full and partial height foundation walls
Level 1:	Mixed use	4-in. concrete slab-on-grade	4-in. concrete slab-on-grade
Level 2:	Office	Post-and-beam framing: Wood bearing walls, glulam beams and columns, prefabricated wood trusses, dimensional lumber and i-joists, 3/4-in. wood sheathing (no concrete topping slab)	Post & beam framing: Wide-flange beams, HSS columns, 5 1/2-in. concrete slab on metal deck
Roof:	Roof	Post-and-beam framing: Wood bearing walls, glulam beams and columns, 4-ply and 5-ply CLT	Post-and-beam framing: Cold-formed steel stud walls, wide-flange beams, HSS columns, open-web steel bar joists, 2-in. acoustic metal deck
Lateral system:		Light-framed wood shear walls	Intermediate reinforced concrete masonry core walls and steel ordinary concentrically braced frames
Volume of structural wood per gross floor area:		0.18 m^3/m^2 (0.60 ft^3/ft^2)	–
Exterior wall systems (from exterior to interior):		Finish, weather barrier, plywood sheathing, wood studs with insulation, gypsum board, interior finish	Finish, insulation, weather barrier, gypsum board, CFS studs with insulation, vapor barrier, gypsum board, interior finish
Special systems:		5-ply CLT elevator core	CMU elevator core
Construction type:		V-B	V-B
Fire rating:		Unrated	Unrated
GWP		**Mass Timber**	**Steel**
Total building $kgCO_2eq$:		273,870	476,371
Total building $kgCO_2eq/m^2$ ($kgCO_2eq/ft^2$):		159 (15)	277 (26)
Substructure $kgCO_2eq/m^2$ ($kgCO_2eq/ft^2$):		108 (10)	111 (10)
Superstructure $kgCO_2eq/m^2$ ($kgCO_2eq/ft^2$):		51 (5)	165 (15)
Construction		**Mass Timber**	**Steel**
Whole building cost:		+2.7%	Baseline
Speed of construction:		Baseline	+17 days (105%)

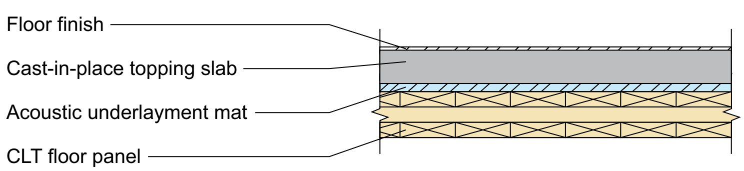
The Burwell Center for Career Achievement

The Burwell Center study compares two building systems for a higher education office and classroom building: mass timber and steel.

Photo: Frank Ooms

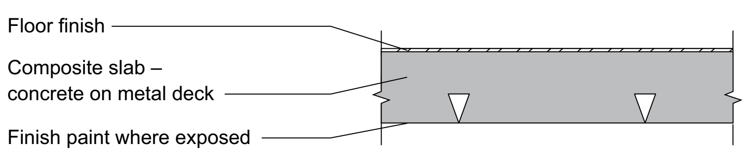
Project Details	
Location:	Denver, CO
Date of construction:	2020
Date of study:	2023, Construction Documents
Owner:	University of Denver
Architect:	Lake Flato; Shears Adkins Rockmore
Structural engineer:	KL&A Engineers & Builders
General contractor:	PCL Construction Services
Mass timber supplier	Nordic Structures
Building use:	Office and classroom
Total size:	3 stories, 22,990 ft^2 (2,136 m^2)

Mass Timber



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

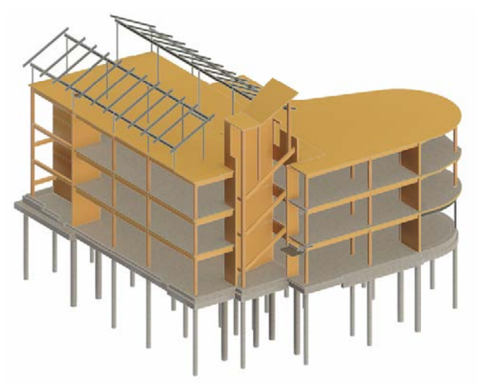
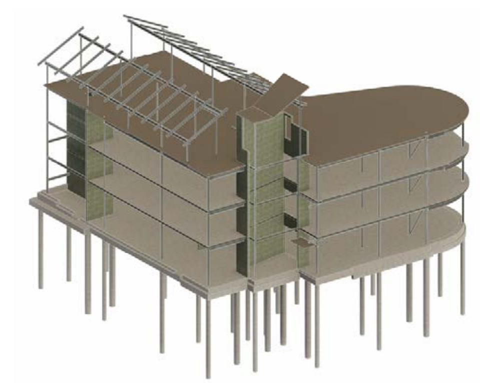
Steel



Note: Floor finish and finish paint are considered architectural finishes and excluded from the LCA.

FIGURE 6: Floor assemblies for the Burwell Center building system alternatives

TABLE 3: Burwell Center summary of design alternatives

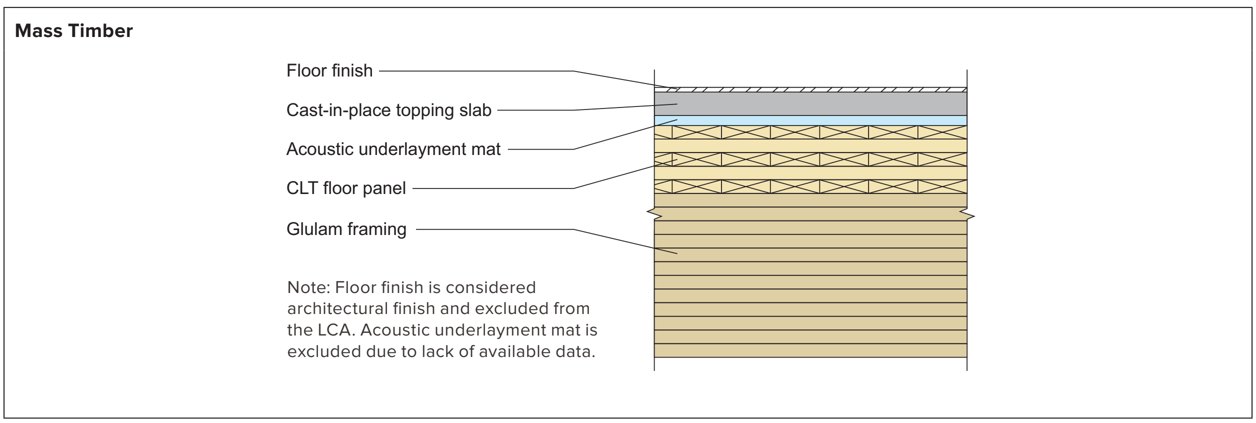
		Systems	
			
Program		**Mass Timber**	**Steel**
Foundations:	–	Concrete drilled piers and grade beams	Concrete drilled piers and grade beams
Level 1:	Mixed use	5-in. concrete slab-on-grade	5-in. concrete slab-on-grade
Levels 2-3:	Office	Post-and-beam framing: Glulam beams and columns, 3-ply CLT, 3-in. concrete topping slab	Post-and-beam framing: Wide-flange beams, HSS columns, 6-1/2-in. concrete on metal deck
Roof:	Roof	Post-and-beam framing: Glulam beams and columns, 3-ply CLT	Post-and-beam framing: Wide-flange beams, HSS columns, 3-in. metal deck
Lateral system:		5-ply CLT core walls	Intermediate reinforced concrete masonry core walls, one steel ordinary concentrically braced frame
Volume of structural wood per gross floor area:		0.21 m^3/m^2 (0.69 ft^3/ft^2)	–
Exterior wall systems (from exterior to interior):		Finish, insulation, weather barrier, gypsum board, cold-formed steel studs with insulation, gypsum board, interior finish	
Construction type:		III-B	
Fire rating:		Unrated primary structural frame, 1 to 2-hour FRR exterior walls, unrated interior partitions	
GWP		**Mass Timber**	**Steel**
Total building $kgCO_2eq$:		479,415	692,397
Total building $kgCO_2eq/m^2$ ($kgCO_2eq/ft^2$):		224 (21)	324 (30)
Substructure $kgCO_2eq/m^2$ ($kgCO_2eq/ft^2$):		67 (6)	65 (6)
Superstructure $kgCO_2eq/m^2$ ($kgCO_2eq/ft^2$):		150 (14)	252 (23)
Construction		**Mass Timber**	**Steel**
Whole building cost:		+6%	Baseline
Speed of construction:		Baseline	+1 month (120%)

Denver Office

The Denver Office study compares two building systems for a higher education office building: mass timber and steel.

Image: Shear Adkins Rockmore

Project Details	
Location:	Denver, CO
Date of construction:	Not yet constructed
Date of study:	2024, Design Development Documents
Architect:	Shears Adkins Rockmore
Structural engineer:	KL&A Engineers & Builders
General contractor:	PCL Construction Services
Mass timber supplier	Nordic Structures
Building use:	Office and classroom
Total size:	4 stories, 98,280 ft² (9,130 m²)



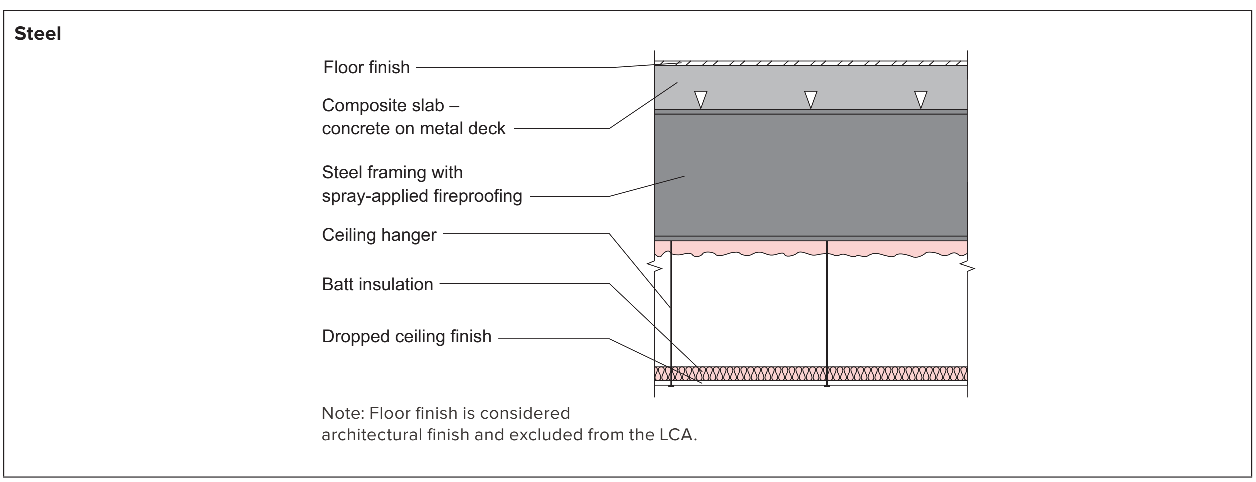
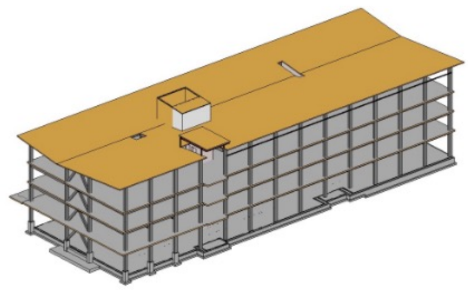
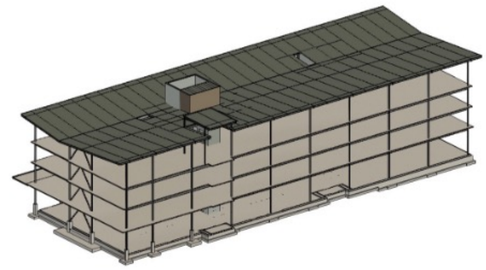


FIGURE 7: Floor assemblies for the Denver Office building system alternatives

TABLE 4: Denver Office summary of design alternatives

		Systems	
			
Program		**Mass Timber**	**Steel**
Foundations:	–	Concrete spread footings, foundation walls	Concrete spread footings, foundation walls
Level 1:	Retail and restaurant	5-in. concrete slab-on-grade	5-in. concrete slab-on-grade
Levels 2-4:	Office	Post, beam, and plate framing: Glulam beams (framing in one direction) and columns, 5-ply CLT, 3-in. concrete topping slab	Post-and-beam framing: Composite wide-flange beams, HSS columns, 6-in. concrete on metal deck
Roof:	Roof	Post, beam, and plate framing: Glulam beams (framing in one direction) and columns, 5-ply CLT	Post-and-beam framing: Wide-flange beams, HSS columns, 3-in. metal deck
Lateral system:		Precast concrete walls, one timber braced frame	Precast concrete walls, one steel ordinary concentrically braced frame
Volume of structural wood per gross floor area:		0.28 m^3/m^2 (0.92 ft^3/ft^2)	–
Exterior wall systems (from exterior to interior):		Finish, insulation, weather barrier, gypsum board, cold-formed steel studs with insulation, gypsum board, interior finish	Finish, insulation, weather barrier, gypsum board, cold-formed steel studs with insulation, gypsum board, interior finish
Special systems:		(1) 7-ply CLT core and (2) 10-in. precast concrete cores	(3) 10-in. precast concrete cores
Construction type:		III-A	II-A
Fire rating:		1-hour FRR primary structural frame, 1-hour interior bearing walls, 2-hour exterior bearing walls, unrated interior partitions	1-hour FRR primary structural frame, 1-hour interior and exterior bearing walls, unrated interior partitions
GWP		**Mass Timber**	**Steel**
Total building $kgCO_2eq$:		1,275,121	2,185,801
Total building $kgCO_2eq/m^2$ ($kgCO_2eq/ft^2$):		140 (13)	239 (22)
Substructure $kgCO_2eq/m^2$ ($kgCO_2eq/ft^2$):		44 (4)	47 (4)
Superstructure $kgCO_2eq/m^2$ ($kgCO_2eq/ft^2$):		95 (9)	192 (18)
Construction		**Mass Timber**	**Steel**
Whole building cost:		+0%	Baseline
Speed of construction:		Baseline	+2.5 months (114%)

Series Trends

The following section details the embodied carbon and economic trends observed across this series. Because the series is limited to four buildings in a limited number of geographic locations and timeframes, trends are not intended to be generalized for all buildings.

Global warming potential (GWP) is the focus of these results, measured in kilograms of carbon dioxide equivalent (kgCO_2eq). Typically, the results are presented as normalized values of GWP per gross floor area (kgCO_2eq/m^2 and kgCO_2eq/ft^2), which allows for comparability of embodied carbon intensity.

In every study, across the various building sizes, uses, and construction types, mass timber buildings demonstrate significant GWP savings and relatively low to zero whole building construction cost premiums, as shown in Figure 8. The total GWP expressed in kgCO_2eq/m^2 for the mass timber buildings ranges from 140 to 224, averaging 182. The total GWP of the alternative buildings ranges from 239 to 324, averaging 273.

This represents a GWP savings of 21% to 43% for the mass timber buildings when compared to their alternative steel and concrete buildings. The whole building construction cost premiums of the mass timber reference buildings range from 0% to 6% with an average of 2.1% when compared to their alternative steel and concrete buildings.

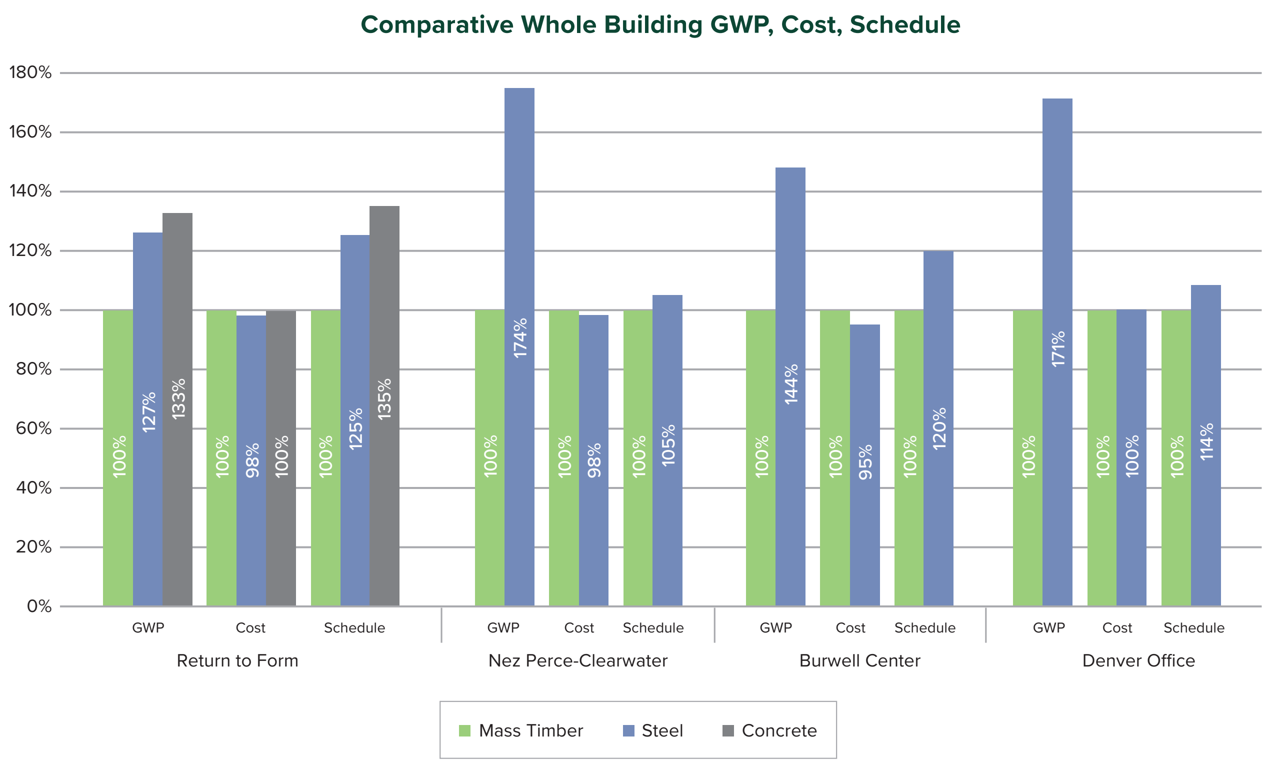


FIGURE 8: Trends of whole building GWP, whole building construction cost, and whole building construction schedule relative to the mass timber reference building.

Illustrating Mass Timber's GWP Savings

The mass timber reference buildings had an average GWP savings of 88 $kgCO_2eq/m^2$. Over a 1,000-square-meter (10,765-square-foot) area, this is equivalent to approximately 21 fewer cars on the road for one year (88,000 kg CO_2eq) for mass timber vs. an alternative structural system (US EPA, 2024). The total GWP savings of the four mass timber buildings sum to 2,195,745 $kgCO_2eq$, which equates to 523 cars off the road for a year and electricity to power 433 homes.*

*This total GWP savings includes embodied carbon data for Return to Form compared to its concrete alternative only.

TABLE 5: Equivalent whole building GWP savings associated with the mass timber buildings

Study Building	Alternative System	Mass Timber System – Equivalent Savings*
Return to Form**	Steel	165 cars 137 homes
	Concrete	207 cars 171 homes
Nez Perce-Clearwater	Steel	48 cars 40 homes
Burwell Center	Steel	51 cars 42 homes
Denver Office	Steel	217 cars 180 homes

= 10 homes   = 10 cars

**Equivalency illustrated in terms of cars driven for one year and electricity to power homes for one year*

***Equivalent values for Return to Form reflect total building GWP savings while the individual study reported equivalent savings for the above-podium system only*

Source: United States Environmental Protection Agency, 2024

Embodied Carbon Trends by Building System

In addition to total building GWP, it is informative to compare GWP of the various building systems and scopes. As described in the Building System Boundaries section, this includes superstructure/above-podium, substructure/podium-and-below, and structural and architectural systems. The purpose of these categorizations is to narrow the focus of comparisons to understand the impacts of structural material system choices and their cascading implications on the GWP impacts of other systems such as the foundations, enclosure, acoustics, fire resistance, and finishes. The ranges of GWP savings in the different system categories are shown in Figure 9. In all cases, the values represent the GWP reduction seen for the mass timber building as compared to the alternatives.

The leftmost value in Figure 9 represents the total building GWP including all systems and components. As discussed, it shows reliable embodied carbon reductions when comparing mass timber buildings to alternative buildings.

Moving right, the next range of values represents GWP reductions for the architectural systems of the total building, including vertical and horizontal enclosures, fire protection and acoustic assemblies, and ceiling finishes. The use of different structural systems results in changes to the architectural components to maintain functional equivalency. These changes are important to capture in the LCA scope for holistic comparisons of the alternative buildings. GWP values for these architectural components range from a 32% reduction to a 9% increase for the mass timber buildings compared to their alternatives. Any increases to the architectural GWP are outweighed by embodied carbon savings of the structure and are discussed further below and within the individual building reports.

The next range of values in Figure 9 isolates the total structural system, including the substructure and superstructure. In contrast to the architectural GWP reductions, the total structural systems see more significant and consistent GWP reductions, ranging from 24% to 55% for the mass timber buildings compared to the alternatives, showing that structural system selection has a large impact on GWP.

The next range is for GWP of the substructure/podium-and-below structural systems, which ranges from a 6% reduction to a 12% increase for the mass timber buildings compared to the alternatives. The increases are summarized in subsequent sections of this report and discussed in greater detail in the individual building reports. Despite increases to the substructure of some mass timber buildings, in all cases, the significant embodied carbon savings seen in the superstructures outweigh these impacts as well any increases in architectural impact.

The last two ranges isolate the superstructure/above-podium systems. The first shows the combined structural and architectural impacts, with reductions ranging from 47% to 69% for the mass timber buildings compared to the functionally equivalent alternative buildings. The second shows the largest reductions of 63% to 118%, occurring when the structural components of the superstructure/above-podium systems are isolated. The extent of these reductions underscores the advantage of mass timber structural systems in reducing structural and total building GWP.

The specific system and material impacts on total GWP are illustrated in Figure 10 for each reference building and its alternatives to illustrate the scope and level of detail of the studies and provide insight into the material makeup of each building. The materials are categorized into three systems: substructure/podium-and-below structural materials, superstructure/above-podium structural materials, and architectural materials. The percentages shown are the GWP reductions for each mass timber building relative to its alternative, and correspond to the ranges of reduction percentages shown in Figure 9.

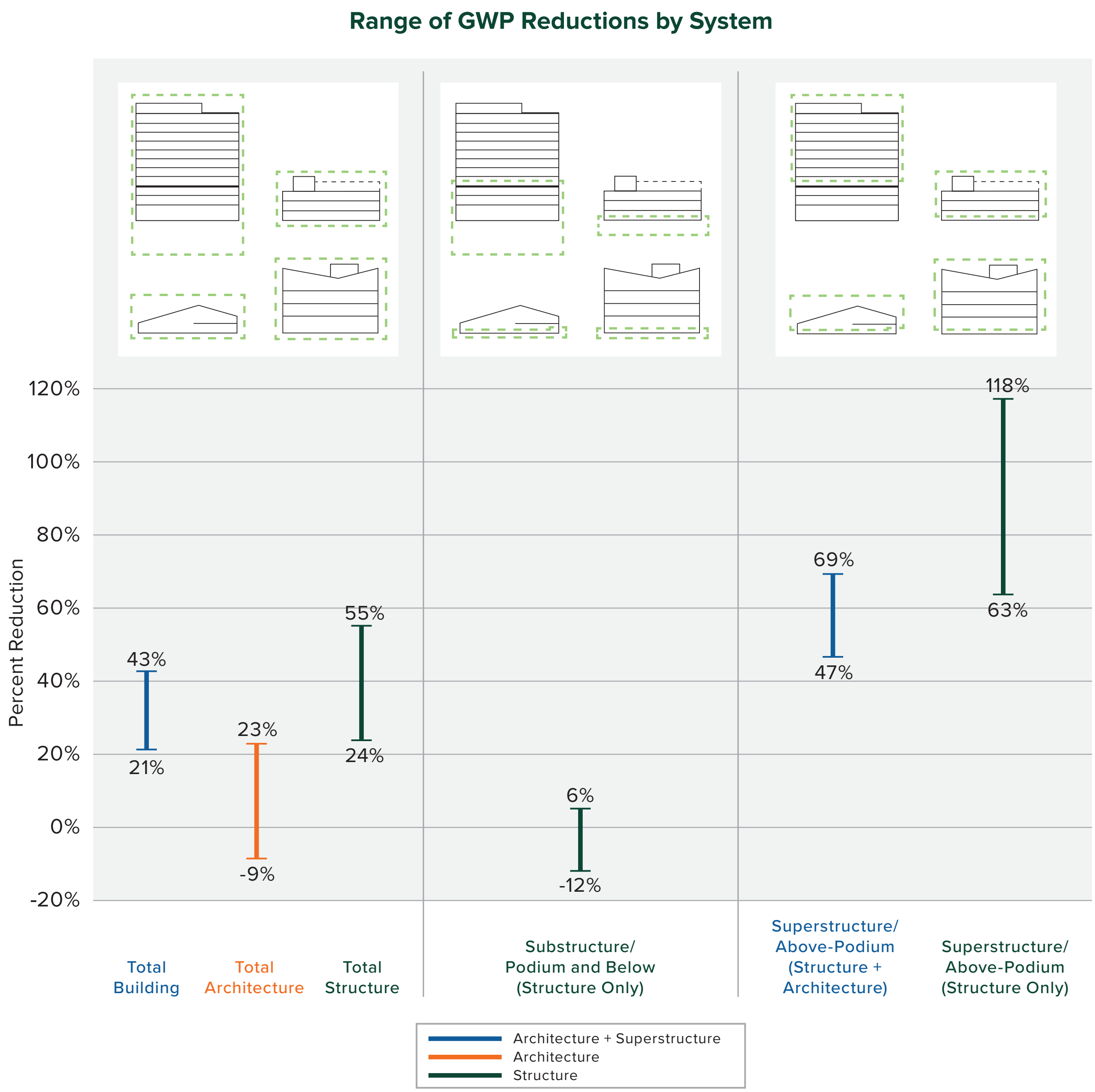


FIGURE 9: Ranges of GWP reductions by system for the mass timber reference buildings compared to their alternative building systems

GWP Comparisons Showing System and Material Breakdowns

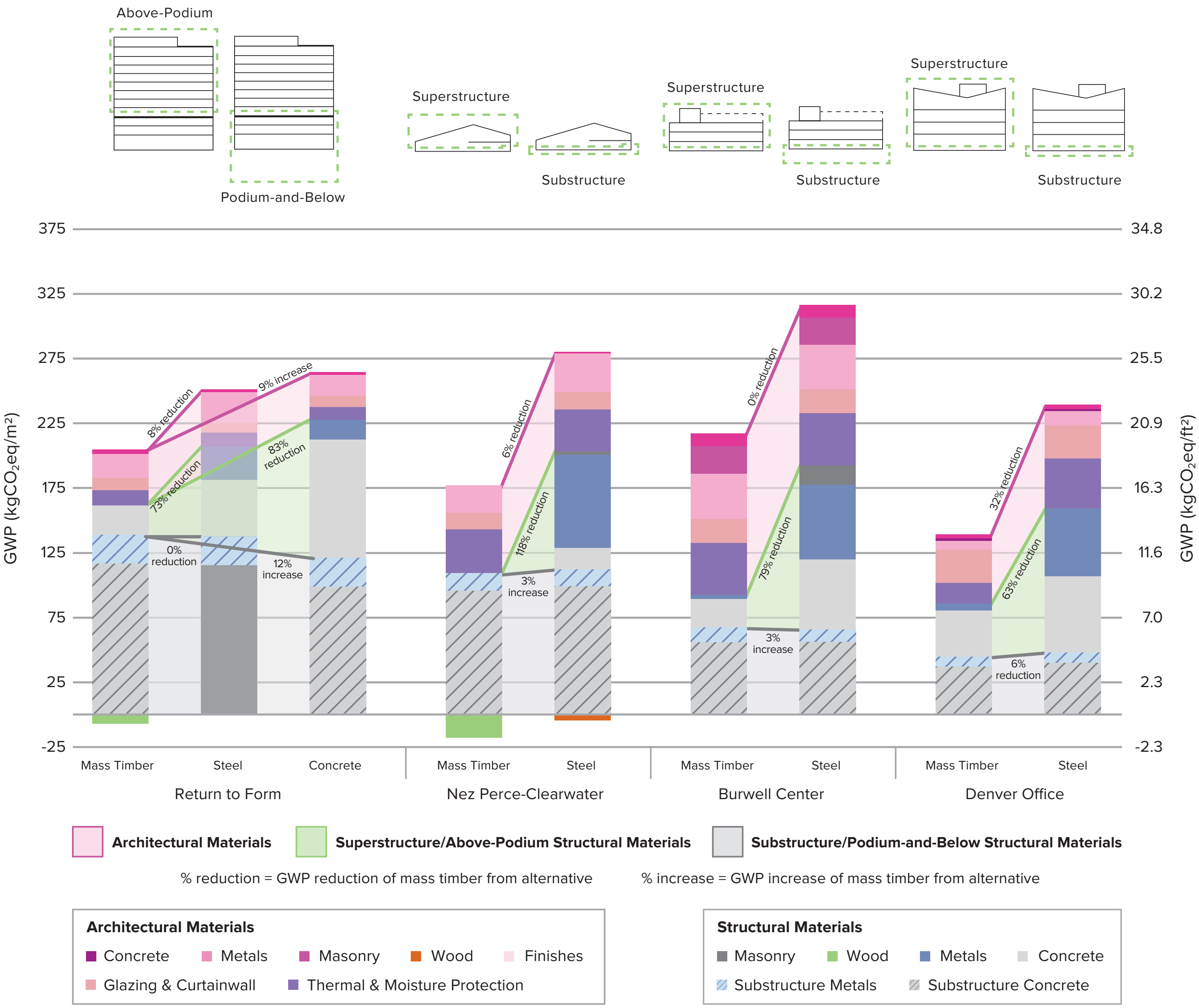


FIGURE 10: Trends of total GWP comparisons by structural substructure and superstructure and architectural components and their material contributions. Note: The wood material GWP for Return to Form and Nez Perce-Clearwater are net negative, shown below the horizontal axis, and therefore, not graphically grouped together with their respective structural and architectural systems, but are included in the % reduction. Positive percentages indicate a GWP reduction from alternative building to mass timber building and negative percentages indicate a GWP increase from alternative building to mass timber building.

Architectural: The architectural systems of the mass timber buildings range from a GWP ($kgCO_2eq/m^2$) of 42 to 131, averaging 74. The alternative buildings range from 38 to 131, averaging 73.

In Figure 10, architectural finishes typically include acoustic ceiling tiles and suspended grids, gypsum board, and stucco. Architectural metals include cold-formed steel studs used for exterior wall non-load-bearing enclosure systems and interior non-load-bearing walls. Architectural masonry includes brick and stone veneers and associated mortar. Architectural concrete includes paver systems.

When comparing the mass timber buildings to their steel alternatives, the architectural GWP is the same or lower in all cases. This is due to an increased amount of architectural material required in the steel alternatives, although the types of materials, quantities, and reasons for this vary. For example, in the buildings in this study, changes in the GWP due to architectural materials are related to building use and construction type, fire protection, acoustics, and building height resulting from increases in floor-to-floor height.

Return to Form is the only study that includes an alternative concrete building, and this is the only instance where the architectural components of the mass timber building have a higher GWP (9% increase) than the alternative. This is primarily because the concrete building is 9 feet shorter than the mass timber building, resulting in less vertical enclosure material.

Structural substructure/podium-and-below: These systems consist of reinforced concrete for all buildings. For the mass timber buildings, the substructure/podium-and-below systems range from a GWP ($kgCO_2eq/m^2$) of 44 to 143, averaging 90. In the alternative buildings, the range is 47 to 143, averaging 82.

The substructure/podium-and-below systems for the alternative buildings were optimized to account for changes to the superstructure structural systems, and while these substructure/podium-and-below systems are significant to total building GWP of each building, they do not have a significant impact on the variation in total building GWP between mass timber and the alternatives. Their significance is in the ability of these systems to dilute the GWP reductions of mass timber structural systems. For example, for Nez Perce-Clearwater, the superstructure shows a 118% GWP reduction; however, when the GWP-intensive substructure is added, the total building reduction drops to 56%.

The podium-and-below system of Return to Form sees a 12% GWP increase in the mass timber building compared to the concrete building due to efficiencies in the concrete system's column grid layout and thinner slab condition at the Level 4 podium. However, the GWP reductions of the above-podium mass timber system significantly outweigh the GWP increases of both the architectural and podium-and-below systems.

Structural superstructure/above-podium systems: In the mass timber buildings, the GWP ($kgCO_2eq/m^2$) of these systems ranges from 51 to 150, averaging 97. In the alternative buildings, the range is 165 to 225, averaging 201.

The superstructure/above-podium systems and materials shown in Figure 10 are isolated in Figure 11 for clarity. The GWP reductions for this system are attributed to less concrete, less steel, and more wood in the mass timber buildings. Wood is an effective material for reducing GWP when used in place of steel and concrete because it has lower functionally equivalent embodied carbon and negative stored biogenic carbon. While most structural material changes and GWP savings are in the gravity-supporting system (floors, beams, and columns), wood can also have significant impacts in lateral systems.[4] Denver Office sees the lowest GWP reduction in the superstructure (63%) and replaces just one of three precast concrete cores from the steel building's lateral system with a CLT core in the mass timber building. In contrast, Burwell Center and Nez Perce-Clearwater replace all CMU cores and see greater superstructure reductions. This underscores the opportunity for lateral system choices in addition to the gravity system to reduce embodied carbon.

The structural wood material in Return to Form and Nez Perce-Clearwater have net negative GWP contributions within the mass timber buildings, indicating that, for the wood material, more biogenic carbon is stored permanently after the end of each building's life than embodied carbon that is emitted over the entire life cycle. Meanwhile, Burwell Center and Denver Office realize very low, net positive GWP impacts even considering longer transportation distances for the wood products.

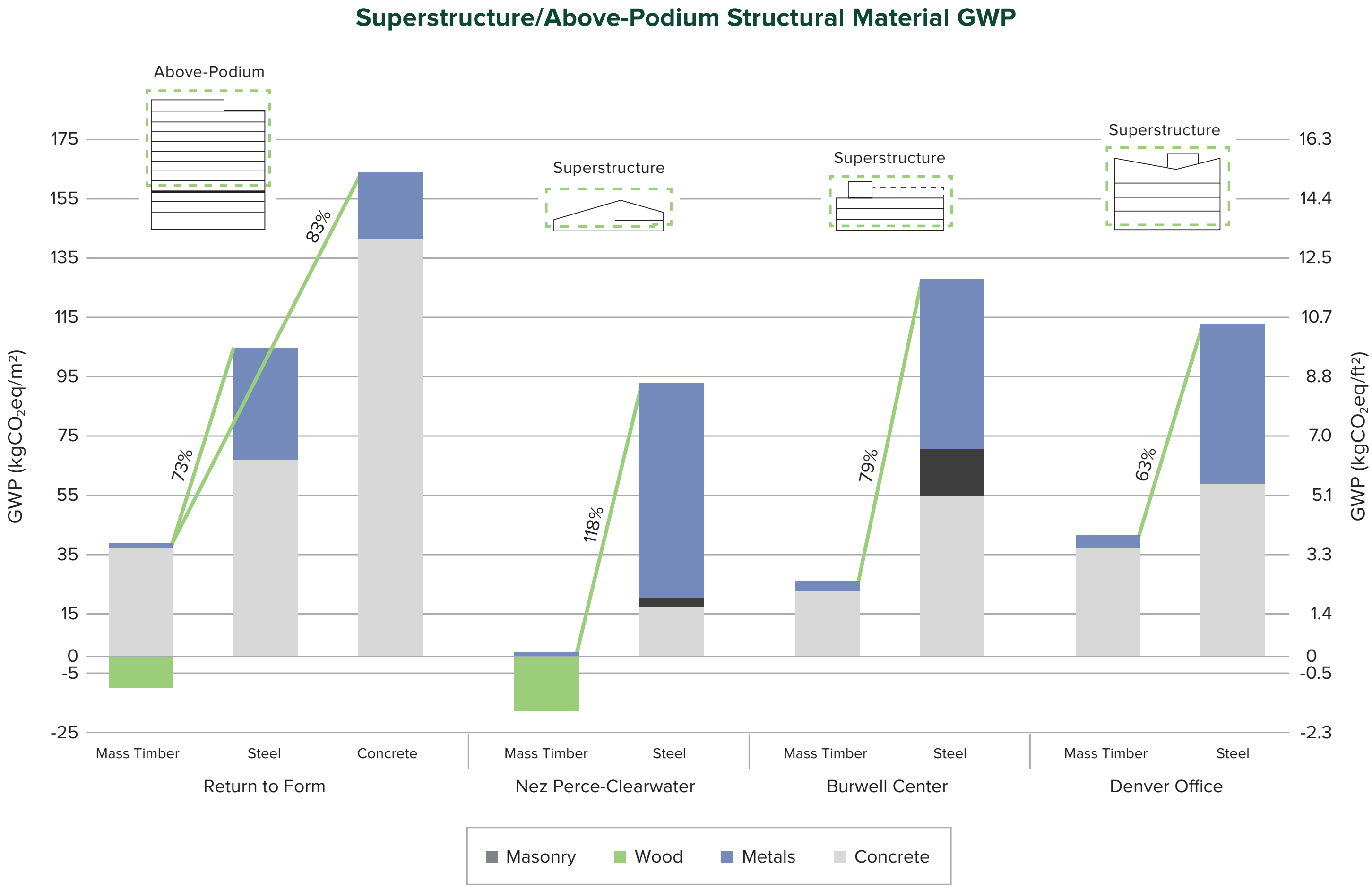


FIGURE 11: Superstructure/above-podium structural material GWP

Figure 11 shows that, even in the mass timber superstructure/above-podium systems of Return to Form, Burwell Center, and Denver Office, concrete and metal are notable material contributors to GWP. A large portion of this impact is from the concrete topping slabs and their steel reinforcement. Nez Perce-Clearwater is the only building in the series without a concrete topping slab. It has the largest structural superstructure GWP reduction of 118% and the only net negative structural superstructure GWP.

The building studies quantify the biogenic carbon content of the wood products, which is termed "stored biogenic carbon." The stored biogenic carbon in $kgCO_2eq/m^2$ ranges from -256 to -165. As shown in Figure 12, the total stored biogenic carbon for the life of the buildings is significant when compared to the total building GWP impact (which includes reductions due to permanently stored biogenic carbon), highlighting the embodied carbon advantage associated with wood's natural ability to store biogenic carbon. As explained in the series introduction, TallyLCA assumes 68.25% of the stored biogenic carbon in wood components is released from the system and 31.75% is permanently stored at end-of-life. The best-case scenario at end-of-life is that the mass timber and other wood material store 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 sum of the stored biogenic carbon during the lifetime of all four mass timber buildings (not permanently stored) is 4,784,541 kgCO_2eq, equivalent to offsetting the embodied carbon impact of 1,139 cars driven for a year or the electricity to power 944 homes for one year (US EPA, 2024). The amount of wood in all four buildings can be regrown in U.S. and Canadian forests in just 16 minutes (WoodWorks, 2024).

As discussed in the series introduction, there is a direct relationship between wood volume and biogenic carbon content, which comprises approximately 50% of the wood by dry mass. Denver Office stores the most biogenic carbon per gross floor area because it has the highest volume of wood, due to its long-span 5-ply CLT system and CLT core walls. Return to Form and Burwell Center follow, with Return to Form using 5-ply CLT floor and roof panels but concrete cores, and Burwell Center using 3-ply CLT floor and roof panels and CLT cores. Nez Perce-Clearwater has the least wood volume and biogenic carbon content because of its mass timber/light-frame wood hybrid system.

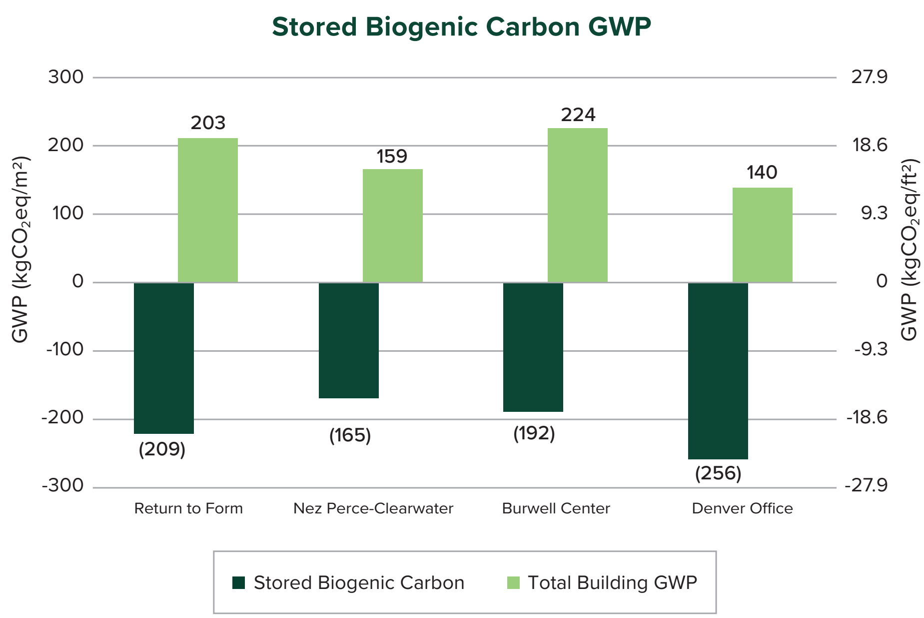


FIGURE 12: Stored biogenic carbon by gross floor area and in total, and total mass timber building GWP (including biogenic carbon)

Cost and Speed of Construction Trends

Although the primary focus of this series is embodied carbon comparisons, it is also important to understand the effects of system and material selections on whole building construction cost and speed to verify the financial feasibility of mass timber construction. Figure 13 compares the cost of the mass timber reference buildings and their design alternatives based on three key aspects: structural raw material, total structure construction including duration, and whole building construction. In each cluster of bars in the chart, the least expensive system is represented as the baseline. This series shows a pattern of significant raw material cost premiums for mass timber buildings but much smaller cost premiums when the speed of construction and whole building construction costs are considered.

Overall, the whole building construction cost premiums range from a minimum of 0% to a maximum of 6%. All four mass timber buildings reported shorter construction durations for both the structure and whole building construction, as well as reduced labor and equipment demands. The shorter construction duration (16% average reduction) can be credited to the ease and efficiency of mass timber erection, reduced interior ceiling finishes, and in some cases the reduction of fire protection materials.

Even Denver Office, with the largest structural raw material cost premium of 126% over its steel alternative, is cost-neutral when considering the whole building construction cost. This implies that there is not a linear relationship between the raw material cost, structure construction cost, and whole building construction cost, and that raw material cost estimates are not a reliable predictor of whole building construction costs. Therefore, holistic cost estimating is encouraged and necessary for the successful implementation of mass timber buildings.

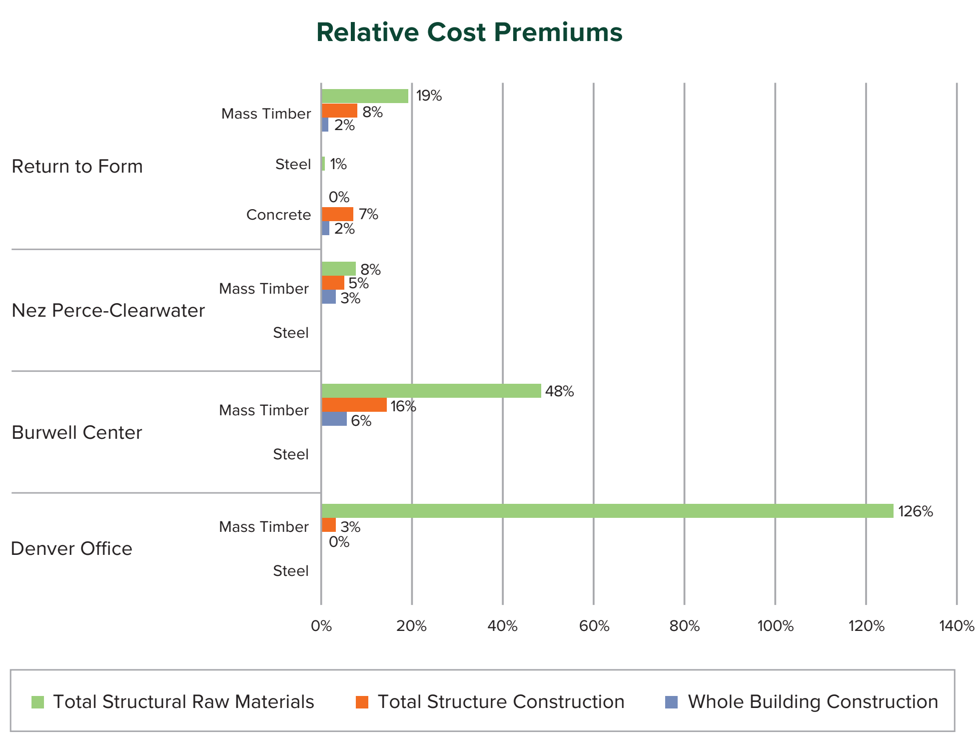


FIGURE 13: Relative cost premium comparisons of raw material, structure construction, and whole building construction. (This figure is based on premiums as compared to the building with the lowest cost at each phase. For Return to Form, the building with the lowest cost varies across each phase.)

A holistic illustration of the GWP, cost, and schedule comparisons are shown in Figure 14 with mass timber buildings as the baseline. For a relatively small dollar cost premium, mass timber buildings can realize significant GWP and schedule savings; however, no specific trend was found between whole building construction cost premium and GWP reduction.

Over time, it is expected that this cost gap can be reduced and potentially overcome entirely as the mass timber market, supply chain, and design and construction expertise mature. In addition, as policies require and/or incentivize the use of lower embodied carbon materials, mass timber systems will become even more advantageous.

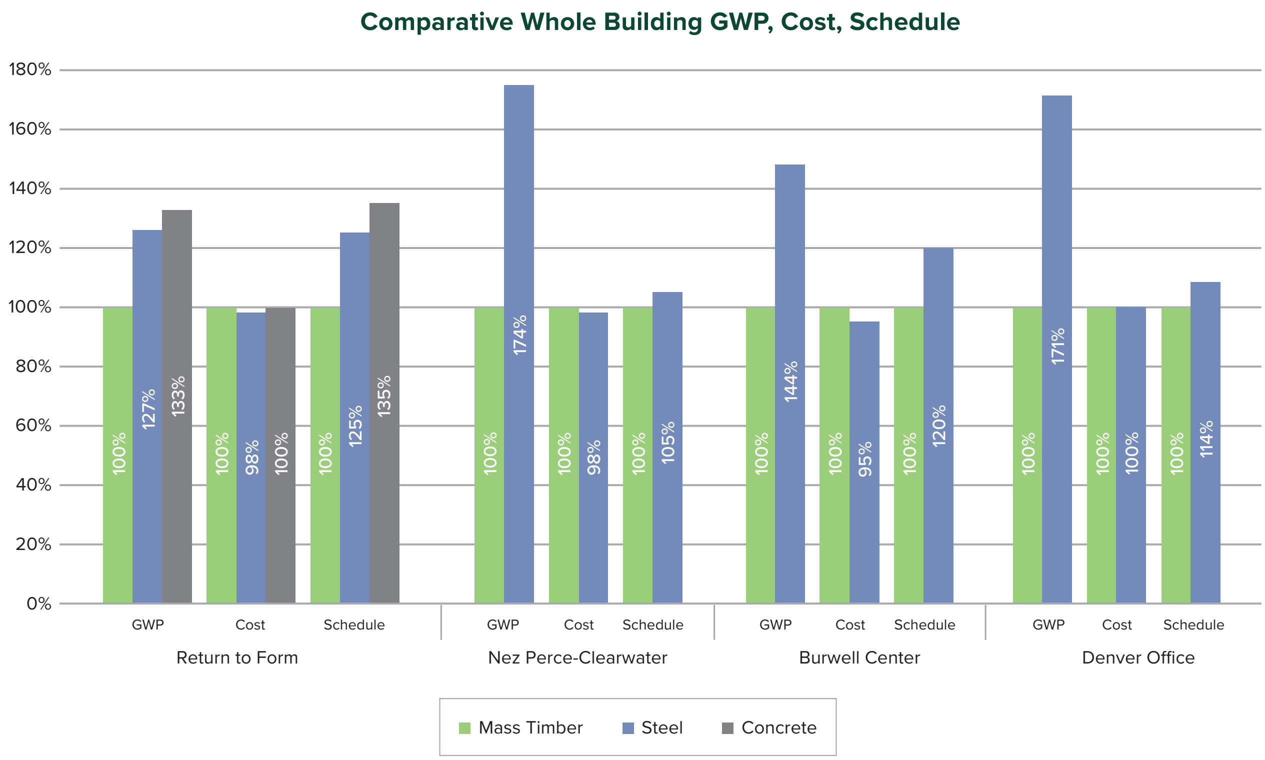


FIGURE 14: Trends of whole building GWP, whole building construction cost, and whole building construction schedule relative to the mass timber reference building

Conclusion

The goal of this series is to illustrate the embodied carbon and economic implications of selecting mass timber structural systems, using real case studies, to support the adoption of mass timber buildings in North America as one of many embodied carbon reduction strategies.

The individual building studies and series trends demonstrate the effectiveness of mass timber systems as an embodied carbon reduction strategy across a range of building sizes, uses, construction types, and framing schemes, with speed of construction benefits and relatively low to zero whole building construction cost premiums. The key trends and conclusions of this series are:

- The total GWP savings of the mass timber reference buildings range from **21% to 43%, and average 32%**, compared to their alternative steel and concrete buildings. The average GWP savings across the four building studies is **88 kgCO_2eq/m^2**.
- When isolating the mass timber and alternative structural systems (i.e., superstructure/above-podium structural systems) for comparison, the GWP savings are even larger, ranging from **63% to 118%**. This highlights the unique opportunity of superstructure system selection to reduce building GWP.
- A comparison of the whole building construction costs,[2] considering construction schedule differences, shows a premium for the mass timber reference buildings ranging from **0% to 6%, and an average 2.1%** when compared to their alternative steel and concrete buildings.
- All four mass timber buildings realized faster construction schedules, with an **average schedule savings of 16%**. This time savings benefits both the dollar cost and embodied carbon impact of construction for the mass timber buildings, though these embodied carbon benefits are not quantified by this study.
- The amount of biogenic carbon stored in the mass timber components during the life of the buildings is significant, ranging from **-256 kgCO_2eq/m^2 to -165 kgCO_2eq/m^2**. The total stored biogenic carbon of all four mass timber buildings is equivalent to offsetting the embodied carbon impact of driving an estimated **1,139 cars for a year or the electricity to power 944 homes for a year** (US EPA, 2024).
- The GWP of the mass timber buildings' substructure/podium-and-below structural systems, which are primarily concrete construction, ranges from 1**2% less to 6% more** than the alternative designs due to variations related to the superstructure systems. This is minor compared to the superstructure/above-podium GWP savings.

For building designers, contractors, owners, and governments considering how best to reduce the embodied carbon impact of building developments, mass timber systems should be considered a viable approach—with the understanding that building life expectancy, material sourcing,[5] and end-of-life pathways[6] for the mass timber material will influence the overall embodied carbon performance. Mass timber structural systems can be implemented broadly today, immediately, while other materials and systems endeavor to improve their embodied carbon over time.

End Notes

1. Functionally equivalent means the same design criteria as the reference systems—i.e., 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. Results for Return to Form's above-podium systems are reported as GWP per above-podium floor area.
3. 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; schedule-related costs like general conditions, labor, equipment and 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.
4. Return to Form structural above-podium results include beams, columns, bearing walls, and floor/roof plates. They do not include the lateral system impacts because the same concrete core walls are utilized in all three buildings.
5. Wood products sourced from North American forests meet the definition of sustainable sourcing per ISO 21930 Section 7.2.11. For more information, see the series introduction.
6. End-of-life considerations are included in the cradle-to-grave LCA results and are based on TallyLCA end-of-life allocation assumptions, as described in the series introduction.

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WW-LCA-06 – Mass Timber Comparative Life Cycle Assessment Series Trends and Conclusions

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