Mass Timber Solutions for Eight Story Mixed-Use Buildings:

A Comparative Study of GHG emissions

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ABSTRACT: Efforts to quantify and reduce greenhouse gas (GHG) emissions of the built environment often neglect embodied emissions, instead focusing on reducing emissions from building operations. Utilizing sustainably sourced mass timber offers low embodied carbon alternatives to traditional concrete and steel structural systems, however the variability in embodied carbon for different mass timber approaches remains understudied. In this study, we used life cycle assessment (LCA) to compare the whole building embodied carbon of nine mass timber design options and two typical concrete and steel reference cases for an eight-story mixed-use building, ensuring structural, acoustic, thermal, programmatic, and fire-rating equivalence between the designs. The study found that the mass timber designs vary significantly, ranging between a 14-52% reduction in whole building embodied carbon from the most impactful reference case, and a 31-73% reduction when considering the structural systems alone. This study demonstrates the value that whole building LCA (WBLCA) provides as a primary driver for low-carbon structural system design and architectural development of mass timber buildings, beyond that of single material comparisons using environmental product declarations (EPDs).

KEYWORDS: mass timber, life cycle assessment, embodied carbon, sustainable design, functional equivalence

Introduction

Efforts to quantify and reduce greenhouse gas (GHG) emissions of buildings have often neglected embodied carbon emissions, instead focusing on reducing emissions from building operations. Unlike operational carbon emissions, however, a significant portion of embodied emissions are released during construction, before the building is even occupied. These impacts, also known as “upfront carbon” critically influence our near-term climate trajectory. As buildings become more efficient and generation grids get cleaner, thereby minimizing operational carbon, the embodied carbon of buildings makes up an increasing proportion of the life cycle emissions. Moreover, as we specify high performance heating and cooling systems, remaining operational carbon emissions are dominated by occupant plug loads and process energy which is more difficult to influence [1]. As a result, it is critical to find ways to reduce the embodied carbon of buildings alongside their operational footprint.

Mass timber construction has emerged within the embodied carbon conversation offering a promise of a lower embodied carbon alternative to traditional concrete and steel structural components and systems. While many benefits of mass timber have been explored (i.e. embodied carbon of structural systems [2], creating demand for sustainable forestry; creating carbon stocks for the lifetime of the building [3]; enabling a shorter construction timeline; offering marketing benefits to the building owner; and offering health and aesthetic benefits to the occupants [4]), a comprehensive quantification of the variability in embodied carbon for different mass timber structural use cases has not been sufficiently studied. More common in the literature is to use a single typical mass timber scenario, compare options that have not been engineered for equal structural design loads, or disregard requirements for fire and acoustics, making the findings less relevant to practitioners. This study instead examines the variability between functionally equivalent design options, which is essential for practitioners to understand the range of possibilities for using mass timber to support decarbonization goals.

Life cycle assessment (LCA) is a quantitative method for estimating the environmental impacts of a product or process over time [5]. When applied to buildings and construction, an LCA model tracks the emissions from material extraction or harvest, transportation, manufacturing or milling, maintenance and use, as well as projected emissions from end-of-life practices like demolition, recycling and disposal [6]. This study reports the embodied carbon of all the design options in terms of Global Warming Potential (GWP) expressed in $kgCO_2e$. This unit, while referencing carbon dioxide, accounts for all greenhouse gases that contribute to global warming by absorbing energy and trapping radiation in the atmosphere, including gases like methane and nitrous oxide in addition to CO2.

In this study, we use LCA to compare the whole-building life cycle embodied carbon of nine mass timber designs and two reference designs for an eight-story mixed-use building (ground floor retail with residential above). While the study did not seek to optimize the reference buildings, we acknowledge that these conventional structural solutions also have significant carbon reduction opportunities that are equally critical to supporting the near-term carbon goals in the construction industry.

This study demonstrates how embodied carbon, used here synonymously with global warming potential (GWP), can be a driver for structural system design and architectural development in all buildings, focusing here on the understudied variability within timber construction. Notably, the study shows how different mass timber structural systems fare in embodied carbon terms when holding program, structural loads, fire rating, acoustical performance, and envelope thermal criteria equivalent in all the options.

Methodology

LCA methodology and professional LCA tools originated in the consumer products industries and are accordingly granular, nuanced, and complicated [7]. For this reason, many architecture, engineering and construction (AEC) professionals find traditional LCA methods to be too tedious to perform and outputs too difficult to interpret [8]. More accessible tools have since become available to fill this gap, and Table 1 describes the pros and cons of three currently available tools that were considered at the outset of this study. Tally was selected as the tool of choice primarily because of its dynamic interoperability with Revit, which was used to document the design options.

Table 1: *Priorities for LCA Workflow*

Life Cycle Assessment Workflow Priorities	**TOOL**		
	Tally	Athena	GaBi
Ease of modelling many options	🟩	🟩	🟥
Quick to implement	🟩	🟩	🟥
Ease of syncing LCA with Revit model updates	🟩	🟥	🟥
Free for commercial users	🟥	🟩	🟥
Fast learning curve (easy-to-use)	🟩	🟩	🟥
Can include cradle-to-grave scope	🟩	🟩	🟩
Can include biogenic carbon accounting	🟩	🟩	🟩
Is populated with material assumptions for US	🟩	🟩	🟩
Provides LCA quality control (i.e. system boundary)	🟩	🟩	🟩
Ability to edit building lifespan	🟩	🟩	🟩
Ability to edit energy of construction	🟩	🟩	🟩
Ability to edit transportation distances	🟩	🟥	🟩
Ability to edit operational utility and water savings	🟩	🟥	🟩
Ability to edit assembly lifetime (replacement rate)	🟩	🟥	🟩
Ability to input EPD without developer assistance	🟥	🟩	🟩

KEY 🟩 **YES** 🟥 **NO**

DESIGN OPTIONS

Eleven design options were developed and compared, with a high level of attention given to maintaining functional equivalence in order to enable appropriate comparison. The first two options (Ref 1-2) documented in Table 2 describe typical concrete and steel structural approaches that were used as the reference cases for comparison, using typical system grids. The following nine options (T1-9) reflect a variety of mass timber structural approaches using 5-ply CLT as a structural slab, varying grid spacing (with spans ranging from approximately 10-20'), altering gravity/lateral systems, and introducing elements of steel to form hybrid systems. T7 and T8 were the only options that did not have concrete core walls in their structural systems. Notably, T7 and T8 also included ground floor steel podiums to accommodate retail program at that level, in order to maintain functional equivalence with the other options. All options were designed to represent typical structural practices at a Level of Detail (LOD) 200, which approximates schematic design, not including structural optimizations.

Table 2. *Design Options Studied*

	Structural Approach	**Struct. Grid Spacing**	**Encap for Fire**	**Comp Slab? Load-bearing façade?**
Ref 1	Concrete Slabs on Steel Deck; Steel Frame; Concrete Cores	>=20'	Yes	CS
Ref 2	Concrete Flat Slab; Concrete Cores	>=20'	N/A	
T1	Timber Post & Plate; Concrete Cores	<= 12'	Yes	
T2	Timber Post, Beam & Plate; Concrete Cores	12' to 20'	Yes	CS
T3	Timber Post, Beam & Plate; Concrete Cores	12 to 20'	Partial	
T4	Timber Post, Beam & Plate; Concrete Cores	12 to 20'	Partial	
T5	Timber Post, Beam & Plate; Concrete Cores	12 to 20'	Char Layer	
T6	Timber Post, Beam & Plate; Concrete Cores	>=20'	Partial	
T7	Timber Floors & Shear Walls; Steel Frame Podium	cellular <=12'	Partial	LBF
T8	Timber Floors; Light Gauge Metal Framing; Steel Frame Podium	cellular <=12'	Partial	LBF
T9	Timber Floors; Steel Frame; Concrete Cores	12 to 20'	Partial	

This LCA study is unique because of the high quality of the design inputs and the multidisciplinary attention to maintaining functional equivalence between the design options. While many LCAs of this sort only consider structure, the modelling scope for this study included structure, foundations, enclosure, and some elements of interior fit-out (interior wall assemblies, fireproofing, and flooring assemblies for acoustic rating). All structural designs were modelled and detailed by professional structural engineers, and the thermal performance of the envelope was designed in accordance with the current Massachusetts energy code. The practicing licensed architectural team provided the assembly details to meet equivalent fire ratings and acoustic performance, as well as floor plan layouts to accommodate the structure and program.

BUILDING ELEMENTS

The study included a whole building LCA comparison of nine mass timber design options and two reference cases. Each variable design option was comprised of the following elements as applicable: columns, beams, foundations, structural walls, floor assemblies, interior walls and fire encapsulation.

Variable reinforcement levels were modelled for the different concrete elements in each option. The necessary encapsulation for fireproofing was included to meet a 2-hour fire rating. Structural steel connections for columns and beams in timber options were not modelled.

The study also included a series of building elements that remained constant between most options. These common elements included the enclosure assemblies (façade and roofing), interior walls, doors and windows. Only options T7 and T8 had significant variability in the enclosure system and interior fit out because their structural approaches doubled as part of the envelope and interiors systems. Mechanical, electrical and plumbing equipment, appliances, finishes and furnishings were not included.

SCOPE

This life cycle assessment included the following lifecycle phases: Product (A1-A3); Transportation (A4); Maintenance and Replacement (B2-B5); and End-of-Life (C2-C4) and Module D. [9] The biogenic accounting method was used within the LCA tool to account for the process of sequestration during the growth phase of the wood (product stage), and later offset by end-of-life practices (incineration, disposal, recycling, etc). The methodology behind the tool is consistent with ISO standards 14040-14044, 21930:2017 and 21931:2010 backed by data from GaBi 8.5 and EPD data, and represents US average industry practices in 2017 [10].

FUNCTIONAL EQUIVALENCE

The functional unit of the study is the single eight-story building. The eleven options are designed to be functionally equivalent in terms of building program, structural performance, envelope thermal criteria, fireproofing for code, and acoustics, shown below.

Table 3. *Project Functional Equivalencies*

Function	Method of ensuring equivalence
Program	All options were designed to accommodate retail at the ground floor with residential units above. A steel podium was designed in Options 7 and 8 to ensure that the ground floor retail, and associated structural span, could be equally accommodated in these options.
Structural Performance	All options were modelled to a LOD200 with specific reinforcement levels for each option, including foundations, using the same design imposed loads.
Fire Rating	All options were modelled with all necessary encapsulation to meet IBC fire code requirements.
Envelope Thermal Criteria	All options included a: • total R-26.5 for insulative materials in opaque assemblies* • U-value of 0.46 for double pane glazing • Window-to-Wall ratio consistent across options: 23% on N/S including curtainwall, and 7% on E/W
Acoustical Performance	Cross-laminate timber floor slabs included layers in all options to ensure vertical Sound Transmission Class (STC) rating of 55.
Building Lifetime	All options were assumed to have a lifetime of 60 years

*meets Massachusetts energy code

The envelope thermal criteria, i.e. opaque construction and glazing, were not optimized for further energy efficiency as this was not the focus of the study.

MATERIAL DATA

Key assumptions for each major material category are included in Table 4, representing typical material selections whenever possible. Wherever a reference EPD is not noted, Tally's LCI data from GaBi was used. Importantly, the concrete in all the options was modelled with 25% fly ash content as is considered responsible practice in the northeast US. The GHG emissions reductions in the mass timber cases would therefore be greater by comparison if no fly ash was included in the reference cases. Similarly, the LCA assumed that nearly all the metal products are substantially recovered, as is typical in the US context, so the GHG emissions reductions from the mass timber options would also be higher by comparison if a project was sourcing steel with lower recycled content.

Table 4. *Key Material Assumptions*

Category	Assumption	Detail
Concrete	Fly Ash	25% in all concrete mixes
	Weight	4001-5000 pounds per square inch (psi) for all structural concrete 4001-5000 psi for lightweight concrete
	Type	standard mix for all concrete, except lightweight concrete topping on metal decking [NRMCA-EPD]
	Lifetime	set to building lifetime
	Reinforcement	concrete reinforcing steel with varying quantity of per structural documentation [CMC-EPD]
Steel	Structural Steel	hot rolled structural steel [AISC-EPD]
	Light Gauge Metal	light structural shapes [CMC-EPD]
	HSS sections	cold rolled steel
	Steel decking	galvanized steel
	Metal stud wall	aluminum extrusions [ASI-EPD]
	Shear studs	1 shear stud per beam linear foot
	Lifetime	set to building lifetime
Wood	Cross-laminated Timber (CLT)	no finish [AMC-EPD, proxied by glulam]
	Glue-laminated Timber (GLT)	no finish [AMC-EPD]
	Lifetime	set to building lifetime
Glazing systems	Glass	double glazed IGUs with air filled cavity
	Frame	extruded aluminum [Kawneer-EPD]
	Lifetime	set to default of 40 years
Gypsum board	Type	specified normal or Type X gyp per fire-rating requirements. Waterproof gyp applied in plumbing walls which remained consistent across options
	Lifetime	set to default of 30 years
Insulation	Type	High density mineral wool used in exterior enclosure [NAIMA-EPD], except for Options 7 and 8 where XPS was used as part of EIFS assembly. High density mineral wool was used in interior applications so remained consistent across options
Floors	CLT floor slab	included 2" cementitious underlayment to represent gypcrete topping material, ¾" closed cell foam as acousti-mat and 2mm of fluid-applied elastomeric compound as acousti-top
	Metal deck	3 inch, 18 gauge symmetrical steel decking with 3.25" lightweight concrete topping with 9.29kg/m^3 of reinforcement
	Slab on Grade	5" slab with 7.42 kg/m^3 of reinforcement.

**low-e coating not accounted for

Tally includes a number of assumptions regarding the End-of-Life (EoL) scenarios of various products to account for emissions realized during demolition, disposal, waste processing and recycling. These assumptions are based on the 2016 WARM Model by the US Environmental Protection Agency and capture typical end-of-life practices for various material types [11]. End-of-life processes for wood products specifically are based on Dovetail Partner's Municipal Solid Waste and Construction Demolition Wood Waste Generation in the United States and Recovery report [12]. Since limited data exists to show how the end-of-life scenario of engineered timber may differ from these scenarios for generic lumber, these figures are applied as a conservative estimate. Given that the infrastructure for recycling metals is already in place, an accordingly high proportion of metals are counted as recovered based on typical recycling rates.

Table 5. *EoL Assumptions from Tally*

Material category	%	EoL scenario
Concrete	55%	Recycled into coarse aggregate
	45%	Landfilled (inert material)
Steel (all types)	98%	Recovered
	2%	Landfilled
Aluminum	95%	Recovered
	5%	Landfilled
Timber (CLT/GLT)	14.5%	Recovered
	22%	Incinerated
	63.5%	Landfilled
Glass	100%	Landfilled
Gypsum board	100%	Landfilled
Insulation	100%	Landfilled

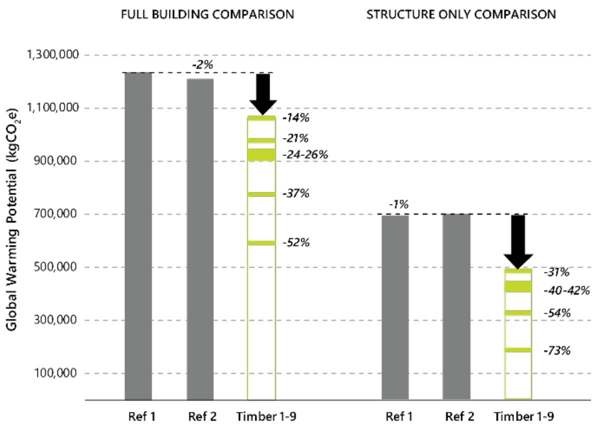
The data used in the study for both the CLT and glulam timber products was based on an environmental product declaration (EPD) published by the American Wood Council in 2013 and CORRIM in 2011 which represent typical US glulam production. CLT was proxied by glulam due to a lack of more specific data. While the industry should soon be able to provide better data for certified wood, preliminary research suggests that FSC and other certified wood products have a smaller environmental footprint than generic products. We therefore expect that using certified wood would further improve the performance of the timber options compared to the reference cases beyond the savings captured by this study [13].

Results

The results for this life cycle assessment are recorded in Global Warming Potential (GWP) expressed in $kgCO_2e$. In this study every timber option yields substantial GWP savings compared to the reference cases, showing that selecting timber for structural systems will generally yield a lower GWP than typical concrete and steel structural systems. As shown in Figure 1, the timber designs vary significantly, from 14-52% in their total GWP reduction from Ref 1 case, and 31-73% GWP reduction when isolating the reduction in structural system. This demonstrates that the particular design approach of a mass timber alternative is critical to realizing the embodied carbon reductions of building with timber.

Timber Options T7 and T8 provide the greatest full building GWP reductions from Ref 1, 52% and 37% respectively, based on the full building comparison. This is primarily because both options were designed without concrete core walls, and because their structural systems doubled as part of their enclosure and interiors systems.

Figure 1. *Full Building and Structural Comparison*



The breakdown in Figure 2 illustrates the specific categories contributing to the total building GWP across every design option. Ref 1, Ref 2 and T9 show a GWP burden for columns and beams due to their steel and concrete members. Notably, the CLT and GLT products, due to credits for sequestration, offset slightly more emissions than they produce making these products slightly negative over the whole life cycle. In options T1-6, columns and beams appear as a small negative, which in this study equates to positive impact and lower net GWP. This negative credit is most evident in T7, where the large volume of CLT in the timber structural walls also reduces the overall GWP footprint of that option.

By contrast, the floors in the timber options are not negative because a two inch slab topping and two acoustic products - acoustimat and acoustitop - are needed to achieve an equivalent acoustic rating as part of functional equivalence, making the impact of the floor assembly a slight carbon burden over the lifecycle of the building.

As noted previously, T7 and T8 show savings in the exterior enclosure as their respective structural systems double as part of their enclosure systems and interior walls. They are also the only two options that included a ground floor steel podium to accommodate the retail long-span requirements, which add a burden to their total GWP.

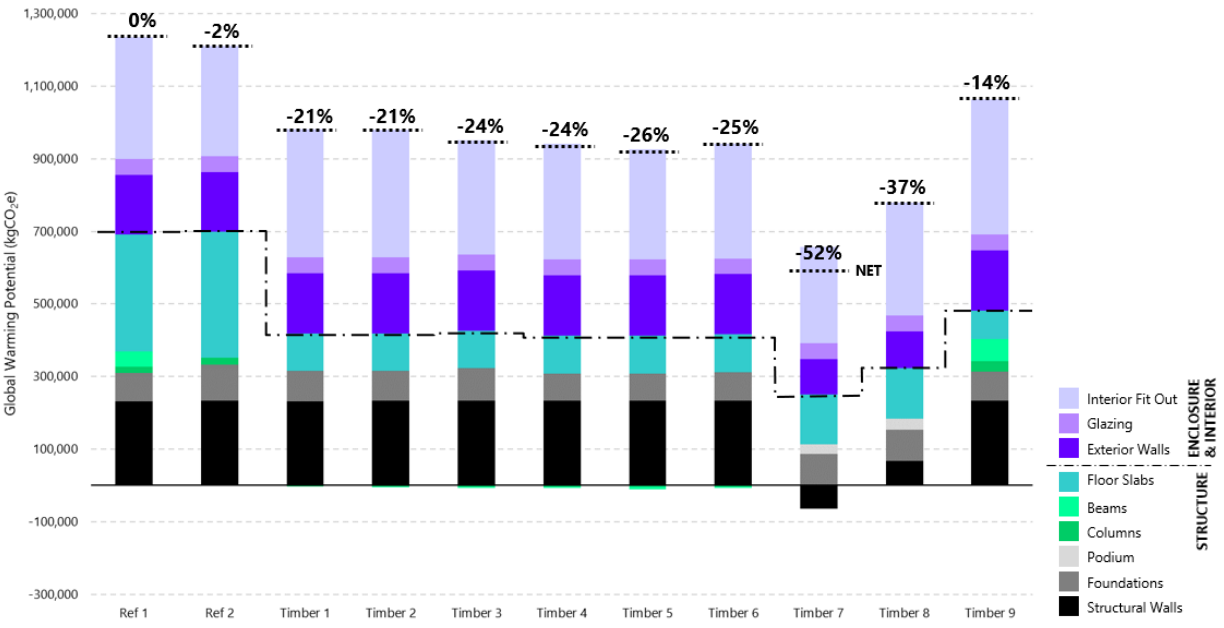


Figure 2. *Full Building Comparison, breakdown by category*

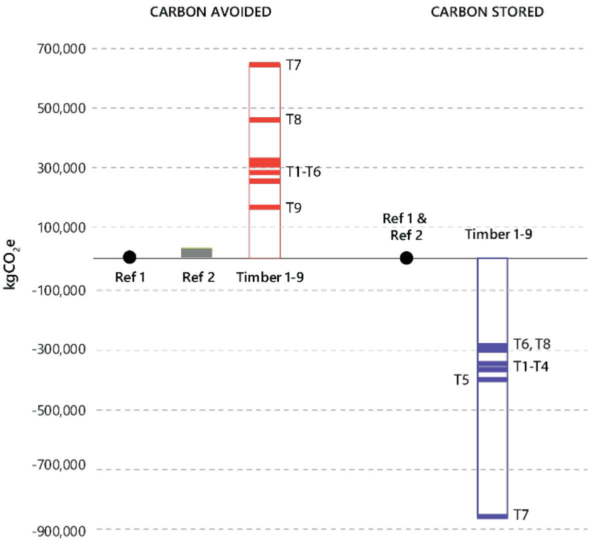
Importantly, this study finds that the timber options do not require significantly more fit out to maintain acoustic and fire performance compared to the reference cases though this is sometimes cited as an obstacle to pursuing mass timber design. Key findings related to this include:

Interior fit-out compared to Ref 1: Timber options T3, T4, T5, T6, T7 and T8 show reductions in interior fit out on the order of 2-4% of total GWP, option T7 shows a 12% reduction in interior fit out in terms of total GWP. Only the timber options with the largest quantity of timber members (T1, T2, T9) require slightly more interior fit-out than Ref 1, equivalent to less than 2% of total GWP for T1 and T2, and 3.3% of total GWP for T9.

Interior fit-out compared to Ref 2: While options T1, T2, T3 and T4, T6, T8 and T9 have slightly more interior fit out (ranging from 1-6% of total GWP), this is due to no gypsum fit-out in Ref 2 as it is not required for fireproofing. While it is expected that most owners/designers would apply gypsum board to concrete, the functional equivalence focus of this study governed its omission in Ref 2.

Finally, in Figure 3, we have also reframed these results in terms of two additional metrics: carbon avoided and carbon stored. Carbon avoided was calculated by subtracting the Global Warming Potential of each option from the Global Warming Potential of Ref 1. Carbon avoided shows the theoretical amount of carbon "not emitted" by choosing any of the alternative options over the Ref 1 scenario.

Figure 3. *Carbon Avoided and Carbon Stored*



Carbon stored refers to the amount of carbon temporarily captured in the engineered timber products in each design option for the duration of the building's lifetime. Carbon stored was calculated by multiplying the wood volume by a constant of sequestration for engineered timber in each of the nine design options. Timber Option 7 shows the greatest storage due to the highest volume of engineered timber. Note that carbon storage is describing a temporary phenomenon, but could play a role in decarbonization strategies that seek to shift forestry yields from shorter to longer-lived wood products.

The juxtaposition of carbon avoided and carbon stored reveals an interesting observation: the option, T7, which avoids the most carbon compared to the Ref 1, is also the option which stores the most carbon in its timber structure. However, option T8 which is the next most successful at avoiding carbon, has one of the lowest values of stored carbon. Here, the light gauge metal design serves to show that combining selective use of timber with other structural innovations, in this case engineering out the structural concrete core walls, can offer impressive GWP savings.

Conclusion

This LCA provides insight into the variability of embodied carbon across an unprecedented range of timber design approaches. The study includes the impacts of the materials required for timber construction to achieve equivalent fire code and acoustic ratings when compared to the reference cases. As the narrative accompanying Figure 2 states, most timber options show a reduction in the impact of interior-fit out materials compared to Ref 1. The timber options mostly showed increases in fit-out compared to the Ref 2 because it did not require gypsum for fireproofing, though it is typical in the industry for concrete flat slab designs to be finished with gypsum even if not for fire. The study therefore demonstrates that despite minimal differences in fit-out required in the timber options to meet acoustical and fire standards, designing with timber offers significant reductions in life cycle GWP compared to typical concrete and steel designs.

In order to study the most representative case, this LCA assumed standard materials to meet codes: foam and elastomeric acoustic layers with a concrete topping applied to the timber floor slabs for acoustical equivalence, and generic Type X gyp with standard metal stud walls for fire encapsulation applied as fire-rating for walls. Given these generic selections, it is likely that lower carbon alternatives could be identified, which would further drive down the emissions of the timber options that require these additional measures.

The typical data for engineered wood used in the study was due to a general lack of more specific data for engineered timber in the field. Future studies with access to more specific wood data would ideally capture the influence of forestry management on this comparative LCA. Future studies should also examine the sensitivity of results to transportation distances of structural products, as this study used Tally's US average transportation distances by material category.

Future work could also introduce more variability in the concrete and steel options to show what reductions are available within these reference systems. Moreover, this analysis could be extended to include the impacts of MEP systems and complete tenant improvements with finishes and furnishings, to better contextualize these reductions and explore how structural system selection drives decisions across design disciplines.

In summary, key findings drawn from these comparisons include:

- Designing with mass timber yields lower whole building embodied carbon compared to the typical steel and concrete approaches studied.
- Engineering out the concrete core walls and taking a cellular approach to the structure (T7,T8) led to the most consequential GWP reductions from Ref 1 ranging from 37-52%.
- Among the options that deployed timber as slabs, beams and columns (T1-T6), using larger grid spacing and exposing timber members (T5) led to the largest GWP reduction at 26% (T1-6,9).
- Fit out for fireproofing and acoustic equivalence did not significantly impact the GWP reductions of any of the timber designs.

The broad finding of this study is that designing with mass timber can offer significant reductions in GWP compared to conventional structural approaches involving concrete and steel designs, ranging from 31-73% of structural system GWP, and 14-52% of whole building GWP. These wide ranges show that varied approaches to structural design in timber buildings yield vastly different reductions in GWP, showing how WBLCA can be used as a primary driver and metric for evaluating timber designs.

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