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. Sustainably sourced mass timber buildings offer a low embodied carbon alternative to traditional concrete and steel structural systems, however the variability in embodied carbon for different mass timber structural systems remains understudied. In this study, we used life cycle assessment (LCA) to compare the whole-building embodied carbon of nine mass timber design options 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 baseline concrete and steel cases, and a 31-73% reduction when considering the structural system alone. This study demonstrates the value that whole building LCA (WBLCA) provides as a primary driver for structural system design and architectural development of mass timber buildings, rather than 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. However, unlike operational carbon emissions, 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 systems. While many benefits of mass timber have been explored and quantified (e.g., 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 systems has not been sufficiently studied. More common in the literature is to use a single typical mass timber scenario, or compare options that have not been engineered for equal structural design loads, making the findings less relevant to practitioners. This study instead examines the variability between functionally equivalent design options, which will be essential for practitioners to understand the range of possibilities for using mass timber to support decarbonization goals.

In this study, we used life cycle assessment (LCA) to compare the whole-building life cycle embodied carbon of nine mass timber designs and two reference designs - one steel and one concrete - for an eight-story mixed-use building (ground floor retail with residential apartments above). While the LCA study did not seek to optimize the concrete or steel 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.

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, transportation, manufacturing, 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 CO_2.

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 for this study. Tally was selected as the tool of choice for this study 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	YES	YES	NO
Quick to implement	YES	YES	NO
Ease of syncing LCA with Revit model updates	YES	NO	NO
Free for commercial users	YES	YES	NO
Fast learning curve (easy-to-use)	YES	YES	NO
Can include cradle-to-grave scope	YES	YES	YES
Can include biogenic carbon accounting	YES	YES	YES
Is populated with material assumptions for US	YES	YES	YES
Provides LCA quality control (i.e. system boundary)	YES	YES	YES
Has co-benefits with assuring Revit model integrity	YES	NO	NO
Ability to edit building lifespan	YES	YES	YES
Ability to edit energy of construction	YES	YES	YES
Ability to edit transportation distances	YES	NO	YES
Ability to edit operational utility and water savings	YES	NO	YES
Ability to edit assembly lifetime (replacement rate)	YES	NO	YES
Ability to input EPD without developer assistance	NO	NO	YES

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 fair comparison. The first two options documented in Table 2 are the concrete and steel options that were used as the baselines for comparison, using typical grids that reflect the building design. All options were designed to represent typical practice at a Level of Detail (LOD) 200, which approximates to schematic design level, not including structural optimizations. The following nine options reflect a variety of mass timber structural approaches using a 5-ply CLT as a structural slab, including varying grid spacing (with spans ranging from approximately 10-20'), altering gravity/lateral systems, and introducing elements of steel, forming 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 in order to accommodate retail at that level, in order to maintain functional equivalence with the other options.

Table 2. *Design Options Studied*

	Structural Material	**Structural Approach**	**Struct. Grid Spacing**	**Encap for Fire**	**Comp Slab? Load-bearing façade?**
Steel	Steel	Post, Beam & Plate	>=20'	Yes	CS
Conc	Concrete	Post+Plate	>=20'	No	
T1	Timber	Post+Plate	<= 12'	Yes	
T2	Timber	Post, Beam + Plate	12' to 20'	Yes	CS
T3	Timber	Post, Beam + Plate	12 to 20'	Partial	
T4	Timber	Post, Beam + Plate	12 to 20'	Partial	
T5	Timber	Post, Beam + Plate	12 to 20'	Char Layer	
T6	Timber	Post, Beam + Plate	>=20'	Partial	
T7	Timber	CLT Walls	cellular <=12'	Partial	LBF
T8	Hybrid	Light Gauge Metal Walls	cellular <=12'	Partial	LBF
T9	Hybrid	Post, Beam + Plate	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, building envelope, and some elements of interior fit-out (interior wall assemblies, roof, ceilings, and fireproofing). All structural designs were modelled and detailed by professional structural engineers, and the thermal performance of the envelope assemblies 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, described in the following sections, as well as floor plan layouts to accommodate the program.

BUILDING ELEMENTS

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

Steel reinforcement levels were modelled for the different concrete elements in each design option. The necessary encapsulation for fireproofing (material/thickness) was modelled to meet a 2-hour fire rating. While the LCA tool used take-offs for metal framing members and connections within some assemblies, like drop ceilings and curtainwalls, 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, referred to here as "common elements". Common elements included the exterior façade assembly, roof assembly, interior walls, doors and windows. Only options T7 and T8 had variability in the enclosure system because their structural approach doubled as part of the envelope system. Mechanical equipment, appliances, finishes, furnishings, and plumbing fixtures were outside the scope of this assessment.

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, ISO 21930:2017 and ISO 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, as described in Table 3. Notably, the envelope thermal criteria - in particular the glazing U-value - are not optimized for further energy efficiency, as this was not the study focus.

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

MATERIAL DATA

A full accounting of the assumptions for each major material category is included in Table 4. These assumptions are meant to represent typical material specifications whenever possible. Importantly, the concrete in all the options was modelled with 25% fly ash content as is considered typical responsible practice by the structural engineers. The GHG emissions reductions in the mass timber cases would therefore be greater by comparison if no fly ash was included in the concrete baseline case. 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, like the less common steel sourced from a basic oxygen furnace, instead of typical electric arc furnaces.

Table 4. *Key Material Assumptions*

Category	Assumption	Detail
Concrete	Fly Ash	25% in all concrete mixes
	Weight	4001-5001 pounds per square inch (psi) for all structural concrete 4001-5001 psi for lightweight concrete
	Type	standard mix for all concrete, except lightweight concrete topping on metal decking
	Lifetime	set to building lifetime
	Reinforcement	concrete reinforcing steel with varying quantity of per structural documentation
Steel	Structural Steel	hot rolled steel
	Light Gauge Metal	light structural shapes
	HSS sections	cold rolled steel
	Steel decking	galvanized steel
	Metal stud wall	galvanized steel
	Shear studs	1 shear stud per beam linear foot (Steel Option)
	Lifetime	set to building lifetime
Wood	Cross-laminated Timber (CLT)	no finish
	Glue-laminated Timber (GLT)	no finish
	Lifetime	set to building lifetime
Glazing systems	Glass	double glazed IGUs with air filled cavity**
	Frame	extruded aluminum frames
	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, 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 acoustic-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/m³ of reinforcement
	Slab on Grade	5" slab with 7.42 kg/m³ 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 2014 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 will further improve the performance of the timber options compared to the steel and concrete baseline cases. [13]. We therefore expect that using FSC certified wood would further improve the performance of the timber options compared to the steel and concrete baseline cases, beyond the savings captured by this study.

Results

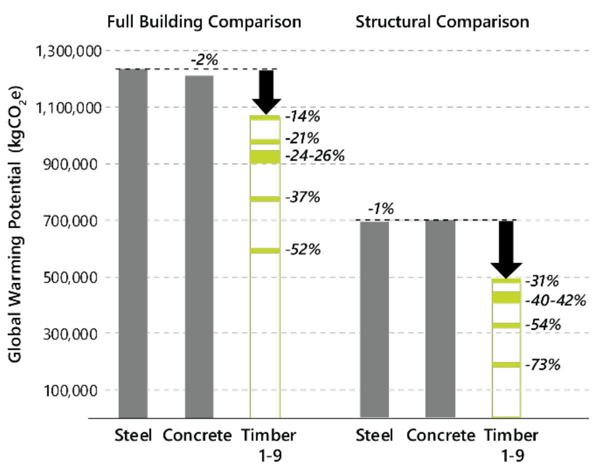
The results for this life cycle assessment are recorded in Global Warming Potential (GWP) expressed in $kgCO_2e$. In this study every timber option yields substantial GWP savings compared to the baseline concrete and steel cases, even when including fireproofing and acoustics, showing that selecting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

Timber Options T7 and T8 provide the greatest GWP reductions from the steel baseline, 52% and 37% respectively, based on the full building comparison. This is primarily because both options were designed to avoid the use of concrete core walls, and also because their structural systems' acted as part of the structural and enclosure systems. 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 project life cycle. For T7, the sheer volume of timber in the design therefore contributes to its reductions.

The breakdown in Figure 2 illustrates the specific categories contributing to the total building GWP across every design option. Steel, Concrete and T9 show a GWP burden for columns and beams due to their steel and concrete members. In options T1-8, columns and beams appear as a small negative, which in this study equates to positive impact and lower net GWP. This is most evident in T7, where the large volume of CLT in the structural walls also reduced the overall GWP footprint of that option.

By contrast, the "floor slab" in the timber options is not negative because a two inch concrete 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 carbon burden over the lifecycle of the building.

Figure 1. *Full Building and Structural Comparison*



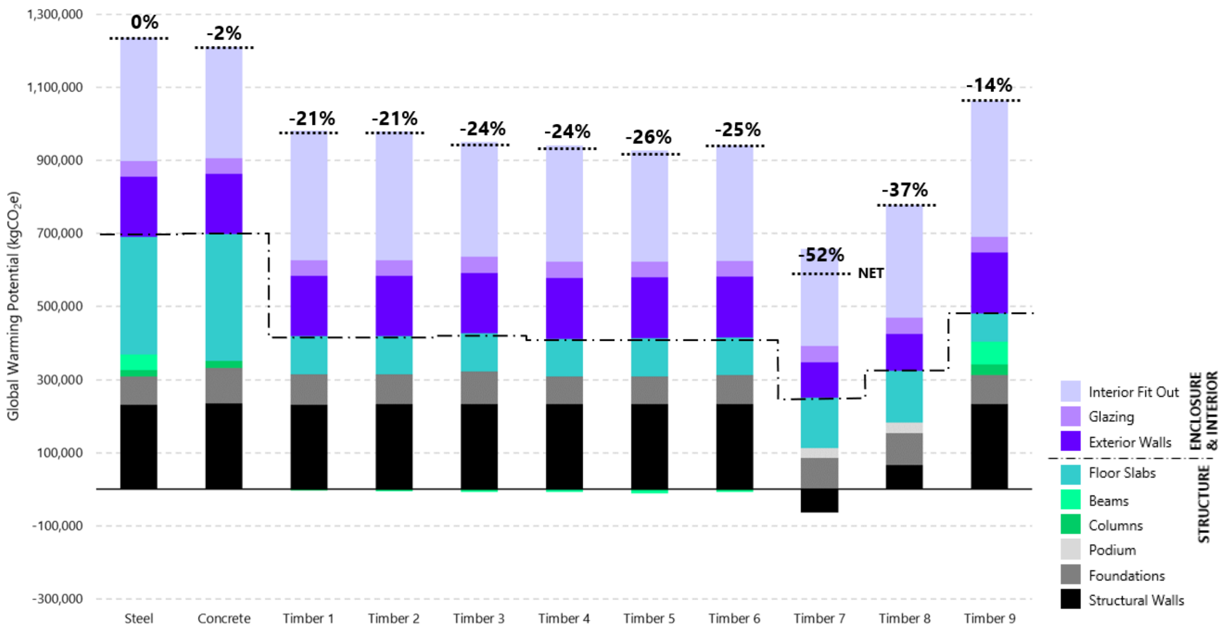


Figure 2. *Full Building Comparison, breakdown by category*

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 added a net burden to their total GWP.

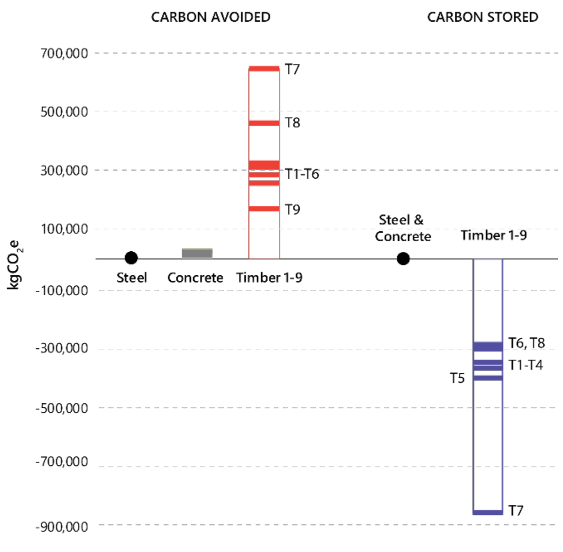
Importantly, this study finds that the timber options do not require significantly more fit out to maintain acoustic and fire performance compared to the steel and concrete options, though this is sometimes cited as an obstacle to pursuing mass timber design. Key findings related to this include:

Interior fit-out compared to steel: 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 the steel option, 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 concrete: 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 the concrete model for fireproofing. However, it is expected that most building owners/designers would apply gypsum board to concrete, even if not required for fire.

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 the highest emitting steel option. Carbon avoided shows the theoretical amount of carbon "not emitted" by choosing any of the alternative options over the most carbon intensive steel scenario.

Figure 3. *Carbon Avoided and Carbon Stored*



Carbon stored refers to the amount of carbon stored 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 this storage quantity is a temporary quantity that only exists for the lifetime of the building.

The juxtaposition of carbon avoided and carbon stored reveals an interesting observation: the option, T7, which avoided the most carbon compared to the steel scenario, 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 core walls, can offer impressive benefits.

Conclusion

This LCA provides insight into the variability of GWP 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 steel and concrete. As the narrative accompanying Figure 2 states, most timber options show a reduction in the impact of interior-fit out materials compared to the steel option. The timber options mostly showed increases in fit-out compared to the concrete option because the concrete baseline did not require gypsum for fireproofing, though it is typical in the industry for concrete 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 Global Warming Potential.

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 may seek to capture the influence of forestry management on this comparative LCA. Future studies should also consider the extent to which transportation of wood, concrete and steel products affects the relative benefits of constructing with timber. Regional production of engineered wood products will likely be needed to achieve the reductions described in this work.

Of the nine timber design options, Timber Option 7 is the most beneficial option with a reduction of 52% in lifecycle Global Warming Potential. By deploying a less intensive light gauge metal structural system and a timber core system, Timber Option 8 also offers a remarkable 37% reduction in Global Warming Potential compared to the steel option, even without the high volume of timber. Future work could also introduce more variability in the concrete and steel options to show what reductions are available within these baseline systems.

Timber options T1-6 also show meaningful reductions in Global Warming Potential, ranging from 21-26% compared to the steel baseline case. Options T1-T4 and T6 illustrate a trend that as grid spacing increases, GWP falls slightly. The larger dimensions of the timber members in T5 to allow it to be exposed rather than encapsulated, remove fit out materials and add timber volume, make it the best performing of the options T1-T6. The worst performing timber option is the hybrid timber-steel design at 14% reduction in GWP form the steel baseline case.

The broad finding of this study is that the redesign of structural systems that would otherwise be concrete and steel to instead be predominantly mass timber results in significant reductions in the GWP of the building's structural system, ranging from 31-73% as shown in Figure 1, and 14-52% of the total GWP for the whole building embodied carbon scope studied. The study demonstrates that LCA can be used as a primary driver for structural system design and architectural development of mass timber buildings.

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