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Life-Cycle Assessment of Environmental Impacts of Mass Timber Buildings in the Northeast Region of the United States

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Abstract

Mass timber building construction is a natural way to mitigate climate change and prevent its associated potential global catastrophic problems. To show the mitigating impact of mass timber, an international research team led by The Nature Conversancy conducted whole-building life-cycle assessments to compare wood structures with corresponding concrete structures for 8-, 12-, and 18-story buildings, based on the 2021 International Building Code, for three regions in the United States. This report covers the set of buildings for one of those regions, specifically the set of buildings designed for the Northeastern region. The mass timber buildings outperformed their concrete alternatives for 13 of the 14 environmental impacts analyzed, especially that of global warming. They were also lighter and stored carbon from the wood used in the building construction. Gypsum wallboard (GWB) was an issue because it contributed to global warming, and the impact increased as the buildings increased in height. GWB was needed because of the 2021 provisions for fire prevention in the international building codes. More research is needed in this area to find alternatives or reduce the environmental impacts of GWB, which will further improve the environmental performance of mass timber buildings. In addition, a local mass timber manufacturing base for all U.S. regions, especially the Northeast, would improve the environmental performance of mass timber buildings.

Keywords: Whole-building life-cycle assessment, engineered wood product, biogenic carbon, environmental impacts

Contents

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Executive Summary

The recent global carbon dioxide (CO_2) emissions report from the International Energy Agency and United Nations Environment Programme stated that the building industry emitted nearly 40% of total greenhouse gases and consumed more than a third of energy produced globally. In response, the building sector has pledged to eliminate all CO_2 emissions from its building activities by 2040 to meet the 1.5 °C climate target. Traditional building materials, such as concrete, steel, and aluminum, are fossil fuel intensive and thus are high-impact materials on the environment. These materials can be substituted with mass timber products, which are low carbon impact, biobased materials, for an opportunity to substantially reduce the embodied carbons in buildings. The Nature Conservancy (TNC) convened a group of international researchers and policy makers from governments and nonprofit organizations with expertise in wood product life-cycle assessment (LCA), forest carbon, and forest products market analysis to address the emissions and energy consumption in mass timber building construction and find urgent solutions to mitigate climate change. These outcomes will be communicated through two multistakeholder advocacy groups: Nature4Climate and the Forest Economy Coalition. In 2017, a paper was published that highlighted many climate solutions including several around forests and active forest management (Griscom and others. 2017. PNAS. 14(44): 11645-11650. https://doi.org/10.1073/pnas.1710465114). Avoiding forest conversion was found to be the most cost-effective. It is globally acknowledged that active forest management, including sustainable harvesting for wood products, prevents the conversion of forests to nonforest land uses. The TNC-led research team hoped to show that increased demand for mass timber would increase the sustainable harvesting of wood products, thus helping to prevent conversion of forest to nonforest land use. Mass timber is a class of adhesively or mechanically laminated wood products such as cross-laminated timber (CLT), glue-laminated timber (glulam), nail-laminated timber, and dowel-laminated timber assembled from dimensional lumber. The result is robust structural panels, beams, and columns that can be used in mid- to high-rise buildings.

Currently, mid- to high-rise building construction commonly uses materials such as concrete and steel, which are energy-intensive to produce, transport, and construct on site. The TNC-led research team hypothesized that increased mass timber construction in cities across the world could significantly reduce environmental impacts and enhance the sustainability of buildings, based on the relatively low embodied carbon, light weight, high carbon sequestration, and renewability of engineered wood products. To test this hypothesis, a series of systematic building LCAs using a cradle-to-gate system boundary (from forest resource to finished building) were conducted to compare functionally equivalent mass timber and concrete buildings in three different regions of the United States.

This report focuses only on a subset of the U.S. regional comparative building LCAs, specifically the set of six buildings that were designed to be built in Boston, Massachusetts, USA. The research team organized these six buildings into three pairs of concrete and mass timber buildings, each pair with matching heights (8, 12, and 18 stories), based on the 2021 International Building Code (IBC) (established types IV-C, IV-B, and IV-A). These heights were chosen to facilitate taller mass timber construction within these ranges. The team designed the bottom 2, 4, and 10 stories of the respective 8-, 12-, and 18-story buildings for commercial office use, while the upper stories were designated as residences. This mixed-use occupancy was based on established market trends throughout cities of the Northeastern United States (the New England region). History has shown that this mixed-use occupancy typically endures for 50 or more years. After that, buildings are usually repurposed, remodeled, or renovated. The mass timber buildings were designed according to a burgeoning structural archetype that covers post-and-beam glulam framing with CLT panels and laterally supports the system with interior cores of CLT panels and perimeter timber-and-steel composite diagonal bracing. The mass timber structural scheme of each pair was compared with a two-way flat slab post-tensioned concrete structure, which has become an established archetype in

cities across the United States for architectural appeal and versatile layouts.

As expected, the mass timber buildings were lighter-weight structures than the concrete buildings. The total weight of the mass timber buildings was 50%, 54%, and 71% of the corresponding concrete buildings (8, 12, and 18 stories, respectively). The use of CLT and glulam in mass timber buildings substituted 75% to 79% of the concrete and 62% to 80% of the rebar used in the concrete buildings. The mass timber buildings, furthermore, had 28% to 50% lower global warming (GW) impact and reduced other environmental impacts relative to the corresponding concrete buildings. Additionally, the mass timber buildings stored 311 to 365 kg CO_2eq per m^2 floor area for as long as the buildings will be in service. Table 1 summarizes the three mass timber building designs, the embodied carbon, and the embodied energy within the scope of this study. The building embodied carbon is the total global warming potential (GWP) associated with carbon emissions from cradle to gate of all manufacturing, transportation, and installation of construction materials. Embodied carbon of the three mass timber buildings ranged from 106 to 149 kg CO_2eq/m^2 of floor area in the buildings. Embodied energy is the cumulated primary energy consumed during the construction of a building and production of building materials, from mining and processing of natural resources to manufacturing, transport, and product delivery. Embodied energy of the three mass timber buildings ranged from 2,451 to 3,007 MJ/m^2.

Introduction

Background

Because of their interest in natural climate solutions, TNC is seeking to understand the potential opportunity to mitigate climate change through the use of mass timber materials in construction around the world. This concept is already supported by many research studies (Kelley and Bergman 2017, Chen and others 2020, Liang and others 2020). TNC organized a multi-institution international collaboration including expertise from forest management, economics, architecture, and LCA to quantify the potential of innovative mass timber materials to improve forest management, revitalize forest economies, and mitigate GHG emissions on a global scale (Gu and others 2021, Puettmann and others 2021, Pasternack and others 2022). Specifically, the team explored the idea that increased demand for sustainable wood products will become a catalyst for reforestation, improved management of forests, and increased mitigation of climate change through the global forest sectors. Through this effort, the team hoped to answer the following questions:

- What is the possible range of climate outcomes associated with increased use of wood in the world construction sector?
- How much do those outcomes vary depending on the specifics of the wood product’s origin, production, and use?
- What scale of impact might a given increase in wood product demand have on wood harvest and forest carbon stocks?

To assess the potential impacts on forests and climate, both positive and negative, of greater forest product utilization, TNC initiated a research program to examine the impacts of building with mass timber. Of particular interest were the ways in which the potential benefits of mass timber might be maximized and the fact that appropriate safeguards can be developed to guard against risks. Because only very large increases in the use of mass timber in the construction sector can potentially make a difference for climate, the study was global in scope and sought to evaluate scenarios in key regions that have begun building 25% to 90% of new buildings with mass timber (i.e., Europe, China, the southern cone of South America, and the United States). Further, because large changes in demand for wood products can impact both local and global trade in forest products, and therefore can impact both local and global forest management, demand changes were assessed using the Global Forest Products Model (GFPM) (Buongiorno and others 2003), a global trade model for forest products. The initial program design was developed through a workshop held in Arlington, Virginia, USA, in July 2018, and consisted of five phases of work:

Phase 1: Comparative LCAs of functionally equivalent mass timber and conventional buildings in selected regions (Europe, China, the southern cone of South America, and the United States) to estimate embodied carbon and carbon

Table 1—Summary of the three mass timber buildings design and result

Stories	Residential/ office–commercial (stories)	Total floor area (m^2)	Total building weight (kg)	Total CLT and glulam used (m^3)	Embodied carbon emission (kg CO_2eq/m^2)	CO_2 storage (kg CO_2/m^2)	Embodied energy (MJ/m^2)
8	6/2	9,476	4,410,304	3,519	106.4	336.3	2,451
12	8/4	14,214	8,166,852	5,729	141.0	365.2	3,007
18	8/10	21,321	13,196,569	7,324	149.1	310.7	2,775

storage from mass timber use at the individual building level. Note: Phase 1 did not consider the impact of demand changes on forest carbon stock; this will be explicitly assessed in Phase 4.

Phase 2: Regional demand assessments to extend the results of individual building LCAs to estimate embodied carbon, carbon storage, and changes in wood demand at varying levels of mass timber penetration (25%, 50%, 90%) in new construction in each of the selected regions (Europe, China, the southern cone of South America, and the United States).

Phase 3: Global trade modelling to estimate how changes in demand for forest products associated with increased penetration of mass timber in each region will directly and indirectly impact global forest product trade flows. (e.g., if 90% of new buildings in region *x* are built with mass timber, where will that timber be supplied from and will other trade flows be displaced?)

Phase 4: Modelling of forest regions identified as likely to be impacted by significant increases or decreases in demand for forest products in Phase 3 in order to assess likely changes in forest area, forest carbon stock, forest structure, and other variables important to determining forest condition. (e.g., if Phase 3 indicates a 10% increase in demand for timber from region *y*, how will forest management, forest area, and other variables be likely to change as a result?)

Phase 5: Integration of the results of Phases 1 through 4 to estimate the total impact on climate and forests of different levels of mass timber use in the selected regions, including the identification of potential risks, associated safeguards, and factors or conditions that enhance or reduce the positive impacts of mass timber use. Results will be communicated through peer-reviewed scientific publications, webinars, briefings for policymakers, and other outlets.

Northeastern U.S. Region Whole-Building Life-Cycle Assessment Study

This report covers a subset of the U.S. regional comparative building LCAs that were performed as part of Phase 1 of the TNC-led research effort. The subset is the six buildings that were designed to be built in Boston, Massachusetts, USA (the Northeastern region of the United States). The research team organized these six buildings into three pairs of functionally equivalent concrete and mass timber buildings, each pair with matching heights (8, 12, and 18 stories), based on the 2021 International Building Code (IBC) (ICC 2021) (established types IV-C, IV-B, and IV-A). Whole-building LCA (WBLCA) studies using a cradle-to-gate system boundary (from forest resource to finished building) were performed on each of the six buildings. The thoroughly detailed report on this regional analysis given here provides a framework for WBLCA of mass timber structures.

Building Design

All the Northeastern U.S. buildings were designed based on projected markets for new mass timber buildings. Therefore, combined residential and office functions were modeled for both timber and concrete buildings in this study. This type of use was expected to endure for the next 50 years. Atelierjones, LLC (Seattle, Washington, USA) designed the mass timber buildings (Fig. 1) proposed to be built in Boston, Massachusetts, in accordance with local building codes that account for geographic and site-specific influence. Table 2 lists the categories, distribution of mixed-use occupancy, heights, and total floor area of the mass timber buildings.

Three functionally equivalent buildings using concrete and steel as the main construction materials were also designed (Fig. 2) and proposed for comparison purpose. A functionally equivalent approach was taken in the building modeling. This did not include elements that are the same for both timber and concrete buildings, such as kitchen appliances and countertops, mechanical soffits, and interior floor finishes.

Figure 1—Mass timber building designs of 8, 12, and 18 stories with mixed use of commercial and residential functions.

Table 2—Design information for the three mass timber buildings

Mass timber construction type	Total stories	Residential stories	Office–commercial stories	Building height (m (ft))	Total floor area (m^2 (ft^2))
IV-C	8	6	2	26 (85)	9,476 (102,000)
IV-B	12	8	4	48 (156)	14,214 (153,000)
IV-A	18	8	10	71 (234)	21,321 (229,500)

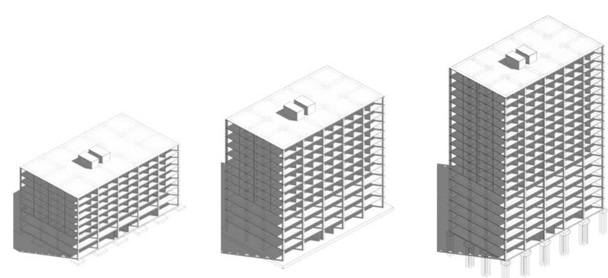

Figure 2—Functionally equivalent concrete buildings of 8, 12, 18 stories with mixed use of commercial and residential functions.

However, wall and floor assemblies that were materially impacted were modelled. This included acoustical ratings (both sound and impact) of floors and common walls and exterior insulation on exterior walls, given the higher thermal performance of mass timber (McLain 2019). Additional consideration was given to the fire and life safety code requirements for mass timber construction, and all mass timber assemblies followed the requisite code performances under the new IBC 2021 provisions for mass timber buildings (ICC 2021, Breneman and others 2022, AWC 2020). Gypsum wallboard (GWB) was assumed as the requisite noncombustible protection, as designed to the hourly ratings of the required wall–floor assemblies per the new International Code Council (ICC) codes. For example, GWB protection is required only for the mass timber assemblies but not for the equivalent noncombustible concrete assemblies.

The exterior wall conditions varied for the mass timber and concrete buildings. As previously discussed, all the mass timber buildings were required to have one layer of noncombustible protection on the exterior face of the exterior mass timber walls. In all the mass timber models, a single layer of Type X, 5/8-in. (15.88 mm) GWB was used. This was not required for the concrete buildings. Similar differences in the amount and kind of insulation for the exterior walls led to the differences in the wall assemblies of each building type.

Each foundation system was designed for a schematic design level of building loads respective to each mass timber and concrete superstructure. Each design resulted from a uniformly applied set of assumptions, including a minimum specified compressive strength of concrete of 27.6 MPa (4,000 lb/in^2) and tensile strength of rebar of 414 MPa (60 lb/in^2). For spread footing foundation design of the 8-story buildings, the allowable soil bearing pressure was set to 144 kPa (3,000 lb/ft^2). The assumed soil subgrade modulus of 67.9 MN/m^2/m (250 lb/in^2/in.) provided a basis for the mat foundation designs. To support 12 stories, the concrete superstructure required a mat 1.22 m (48 in.) thick, while the mass timber superstructure required a mat 0.91 m (36 in.) thick. A pile capacity of 90.7 metric tons (100 tons) provided the basis for deep foundation designs to support the 18-story pairs. Table 3 shows that spread footing, mat, and pile foundation types were correlated to the respective 8-, 12-, and 18-story building heights to facilitate direct comparisons. In every pairing, the heavier concrete superstructures required larger volumes of concrete and reinforcing steel than the lighter timber superstructures. Table 4 shows the viable foundation options for each superstructure. In this group of case studies, only the shortest concrete superstructure could be practically supported on spread footings. Only the 18-story concrete superstructure necessitated a pile foundation. Because of the relative light weight, all heights of the mass timber superstructures could have been supported on spread footing, although at 18 stories, the mat or pile foundations became more cost competitive. For many projects, avoiding deep foundations could provide enough cost incentive to sway the decision toward a mass timber superstructure. The research team, however, decided to simplify the foundation comparisons and adhere to Table 3 to focus on the LCA impacts.

Methodology

Goal and Scope

The WBLCA approach applied in this study follows the EN 15978 (ECS 2012) and ISO 21930 (ISO 2017) standards to analyze the material effects of structure, envelope, and interior walls of the designed buildings. These EN and ISO standards define the building life-cycle stages (Fig. 3) from Product (A1-A3), Construction (A4-A5), Use (B), End of Life (C), to Beyond System (D) stages (Stage D is not shown in Fig. 3). The scope of this WBLCA is a cradle-to-gate (building constructed) analysis of the building materials, transportation, and construction process before reaching the building's completion. The goal of this study was to analyze the environmental life-cycle impacts of the three mass timber buildings from the Product and Construction stages (A) and compare the results to functionally equivalent concrete buildings as previously described.

Functional Unit

The functional unit for this WBLCA study is defined as "providing 1 m^2 of living floor area in the building designed for the U.S. Northeastern region".

Table 3—Foundation types for each building pair by number of stories

	Building superstructure[a]	
Stories	Mass timber	Concrete
8	S	S
12	M	M
18	P	P

[a]S, spread footing (shallow); M, mat foundation (shallow); P, pile foundation (deep).

Table 4—Viable options for foundation types based on superstructure weights

	Building superstructure[a]	
Stories	Mass timber	Concrete
8	S	S, M
12	S, M	M, P
18	S, M, P	P

[a]S, spread footing (shallow); M, mat foundation (shallow); P, pile foundation (deep).

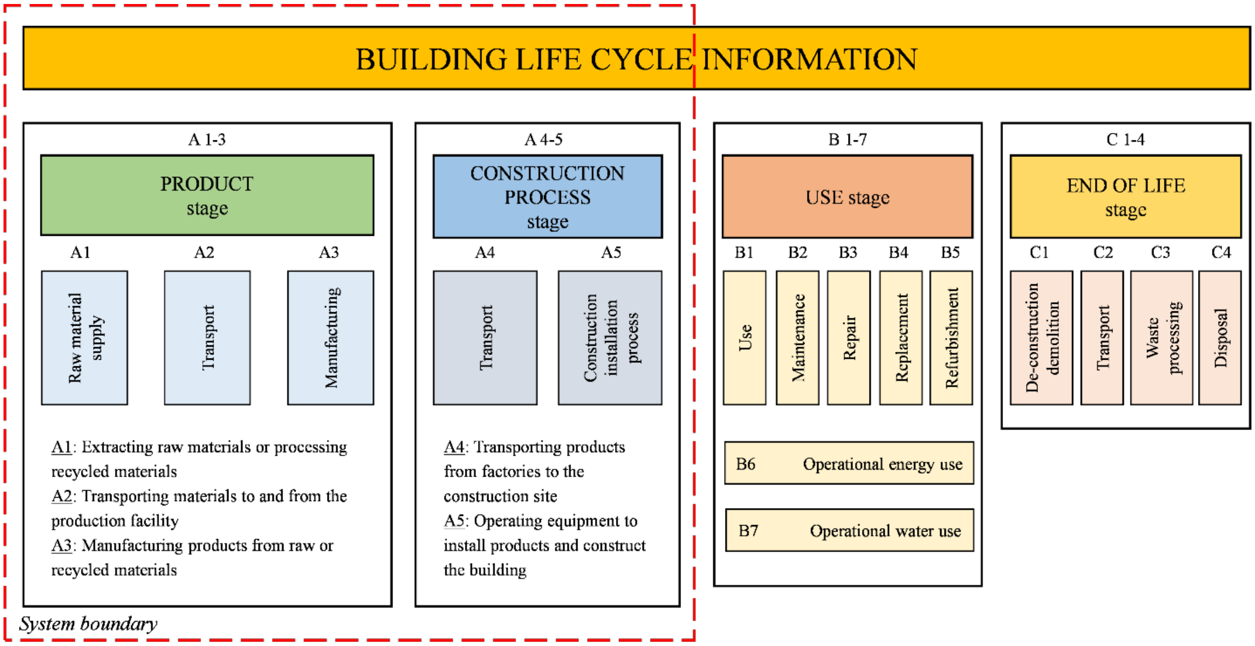

Figure 3—Life-cycle stages and their information modules for the whole-building LCA (the dotted line defines the system boundary for this study).

System Boundary

The system boundary defines which activities in the specified life-cycle stages are to be included in the analysis (Fig. 3). This study covered only stage A, which includes modules A1-raw material supply, A2-transportation of raw materials to product manufacturing site, A3-product manufacturing, A4-transportation of products to building construction site, and A5-construction and installation of buildings. Life-cycle stages B and C were excluded from this study. This study compared the mass timber buildings with concrete alternatives in terms of material choices for the environmental impacts. Thus, only stage A was included. Although end-of-life treatment is also material–product driven and substantially influences a building’s embodied carbon estimations, it was not included in this study because the focus was on the upstream embodied carbon using attributional LCA analysis.

Life-Cycle Inventory of Building Materials

To model the WBLCA, materials used in the building were aggregated together for the product stage (A1-A3) life-cycle impacts. The life-cycle inventory (LCI) of each building material measures inputs of materials and energy use to produce one functional unit of the defined product and transportation needed within the defined boundary system. It also measures outputs of combined emissions to air, water, and land for the total impact assessment. The product’s inventory can be built with practical manufacturing data, published literature, or process simulations if manufacturing data are unavailable.

In this study, the LCI for each building material in the designed mass timber and concrete buildings was either collected from the available LCI database for North America or built with the known manufacturing process modified with regional data in SimaPro software for this project (PRé Consultants 2020a). SimaPro is an internationally recognized, science-based tool that provides LCA practitioners with included databases and consistent methodology to effectively analyze the environmental impacts from materials and processes in all the different stages of building or a products life cycle. This information empowers a solid decision to improve designs for a better environment.

Life-Cycle Impact Assessment

Life-cycle impact assessment (LCIA) uses predefined methods to quantify the type and extent of environmental and human health impacts that may arise based on the collected data in LCIs. In this study, the LCI data of each building material was compiled and the impacts were assessed using the North American tool for the reduction and assessment of chemical and other environmental impacts (TRACI) method for environmental impacts (Bare 2011) and the cumulative energy demand (lower heating value (LHV)) v1.00 method for energy demand quantifications (PRé Consultants 2020b). This LCA was modeled in the SimaPro 9.0 software following the ISO 14040 and ISO 14044 environmental management standards (ISO 2016a,b). A total of 14 environmental indicators, shown in Table 5, were chosen for this WBLCA study.

Table 5—Selected impact indicators reported

Reporting category per tables E1-E5 in ISO 21930:2017	Indicator name	Abbreviation	Unit
Core mandatory impact indicators	Global warming potential, fossil	GWP	kg CO_2eq
Core mandatory impact indicators	Depletion potential of the stratospheric ozone layer	ODP	kg CFC11eq
Core mandatory impact indicators	Acidification potential of soil and water sources	AP	kg SO_2eq
Core mandatory impact indicators	Eutrophication potential	EP	kg PO_4eq
Core mandatory impact indicators	Formation potential of tropospheric ozone	SFP	kg O_3eq
Core mandatory impact indicators	Abiotic depletion potential for fossil resources	ADPf	MJ, NCV
Core mandatory impact indicators	Abiotic depletion potential (element) for fossil resources	ADPe	kg, Sbe
Core mandatory impact indicators	Fossil fuel depletion	FFD	MJ surplus
Use of primary resources	Renewable primary energy carrier used as energy	RPRE	MJ, NCV
Use of primary resources	Nonrenewable primary energy carrier used as energy	NRPRE	MJ, NCV
Mandatory inventory parameters	Consumption of freshwater resources	FW	m^3
Indicators describing waste	Hazardous waste disposed	HWD	kg
Indicators describing waste	Nonhazardous waste disposed	NHWD	kg
Additional inventory parameters for transparency	Biogenic carbon removal from product	BCRP	kg CO_2eq
Additional inventory parameters for transparency	Biogenic carbon emission from product	BCEP	kg CO_2eq
Additional inventory parameters for transparency	Biogenic carbon emission from combustion of waste from renewable sources used in production processes	BCEW	kg CO_2eq
Additional inventory parameters for transparency	Calcination carbon emissions	CCE	kg CO_2eq

Results

This section addresses the main results of the WBLCA, including the emissions and the energy consumed in the construction from cradle to gate, as well as the material quantities in the mass timber and concrete building designs. The overall impacts are summarized by an assessment of GWP and carbon storage in the mass timber buildings.

Bill of Materials

The materials used in all building designs were obtained from the blueprints of the building information modeling (BIM) process and are summarized in Table 6. The majority of the concrete and rebar used in the concrete buildings was replaced by CLT and glulam in the mass timber buildings. All timber buildings required less concrete but did require additional materials such as gypsum concrete on top of CLT floors for acoustical and vibrational protection, as well as additional layers of GWB for fire and acoustic performance in the CLT walls. For interior walls, timber buildings required additional brace framing, whereas concrete buildings required the use of rebars. The mass timber buildings used more wood, insulation, and gypsum materials and less concrete and rebar than corresponding concrete buildings. For instance, the 8-story mass timber building used 2,761 m^3 CLT and 758 m^3 glulam that substituted 79% of the concrete and 91% of the rebar in the corresponding concrete building. The 12-story mass timber building used 4,522 m^3 CLT and 1,207 m^3 glulam that substituted 77% of the concrete and 81% of the rebar in the corresponding concrete building. And the 18-story mass timber building used 5,591 m^3 CLT and 1,733 m^3 glulam that substituted 67% of the concrete and 62% of the rebar in the corresponding concrete building.

All the building materials were converted into mass (kilograms) using the material density property if they were quantified in volume by BIM. Table 7 shows building mass by assembly type for each of the three mass timber buildings and corresponding concrete buildings. The mass of the building materials was used to calculate the impacts of product transportation (A4) and construction installation (A5). The mass timber buildings were lighter in weight and amounted to 50%, 54%, and 71% of the corresponding 8-, 12-, and 18-story concrete buildings, respectively. The 12-story building used a mat footing foundation, which required more concrete and rebar than the foundation designs for the 8- and 18-story buildings and skewed the proportions of foundation weight to total building weight. The LCA criteria assessed foundations based on material quantities, without accounting for the increased costs of driving or drilling piles.

In each building, the individual floors weighed approximately the same. The weight of foundations, columns, walls, and diagonal bracing elements in the

Table 6—Bill of materials comparisons of mass timber and concrete buildings

			8-story		12-story		18-story	
Assembly	Material[a]	Unit	Mass timber	Concrete	Mass timber	Concrete	Mass timber	Concrete
Columns and beams	Concrete	m^3	—	93	—	385	—	586
	Glulam	m^3	758	—	1,207	—	1,733	—
	Rebar	kg	—	59,392	—	139,608	—	285,609
Exterior walls	Aluminum stud	kg	—	738	—	1,550	—	2,400
	CLT	m^3	172	—	364	—	564	—
	3-5/8-in. fiberglass mat	m^2	—	1,638	—	3,479	—	5,387
	5/8-in. gypsum board	m^2	1,638	1,638	3,479	3,479	5,387	5,387
	5-in. mineral wool	m^2	1,638	—	3,479	—	5,387	—
	1-1/2-in. polystyrene	m^2	—	1,638	—	3,479	—	5,387
Floors	3/8-in. acoustic mat	m^2	8,229	—	12,053	—	18,277	—
	CLT	m^3	1,437	—	2,105	—	3,192	—
	Concrete	m^3	372	2,293	—	2,865	370	6,894
	Gypsum concrete	m^3	418	—	612	—	928	—
	3/8-in. PE vapor barrier	m^2	1,220	1,214	1,533	1,537	1,214	1,229
	Rebar	kg	5,401	41,697	—	54,551	5,388	87,245
Foundation	Concrete	m^3	367	674	1,402	1,874	601	818
	Rebar	kg	12,498	20,366	102,743	187,233	28,741	34,696
Walls	CLT	m^3	1,152	—	2,053	—	1,835	—
	Concrete	m^3	—	516	—	961	1,474	1,419
	3-5/8-in. fiberglass mat	m^2	280	3,511	500	5,934	757	8,830
	5/8-in. gypsum board	m^2	13,724	24,041	74,381	40,707	175,872	60,959
	3-in. mineral wool	m^2	3,287	—	5,617	—	8,317	—
	Rebar	kg	—	73,125	—	145,206	202,066	214,477
	Steel stud	kg	8,112	16,302	13,182	25,974	19,812	38,844

[a]1 in. = 25.4 mm; CLT, cross-laminated timber; PE, polyethylene.

Table 7—Whole-building weight by assembly for three mass timber and three concrete buildings

	Whole-building weight (kg)[a]		
Building assembly	8 stories	12 stories	18 stories
Mass timber buildings			
Columns	356,530 (8.1%)	568,072 (7.0%)	815,335 (6.2%)
Exterior wall	116,949 (2.7%)	248,335 (3.0%)	384,517 (2.9%)
Floor	2,332,204 (52.9%)	2,154,134 (26.4%)	4,112,569 (31.2%)
Foundation	855,959 (19.4%)	3,323,465 (40.7%)	1,410,199 (10.7%)
Interior wall	748,662 (17.0%)	1,872,846 (22.9%)	6,473,949 (49.1%)
Total	4,410,304 (100%)	8,166,852 (100%)	13,196,569 (100%)
Concrete buildings			
Columns	272,886 (3.1%)	1,023,691 (6.8%)	1,633,500 (8.8%)
Exterior wall	26,425 (0.3%)	56,160 (0.4%)	86,948 (0.5%)
Floor	5,323,313 (60.9%)	6,653,324 (44.2%)	10,821,963 (58.0%)
Foundation	1,566,335 (17.9%)	4,493,047 (29.8%)	1,915,227 (10.3%)
Interior wall	1,548,281 (17.7%)	2,841,543 (18.9%)	4,205,965 (22.5%)
Total	8,737,240 (100%)	15,067,766 (100%)	8,663,603 (100%)

[a]Percentage weight of whole building shown in parentheses.

vertical planes typically increased in proportion to building height. Consequently, floor weight exhibited the greatest proportion of total building weight in the shortest (8-story) mass timber building, accounting for 53%. In the 12-story mass timber building, the foundation accounted for 41% of total building weight, whereas in the 8- and 18-story mass timber buildings, the foundation accounted for 19% and 11% of the total weight (Table 7). This was caused by the mat footing design for the 12-story building, which used more cement and rebar to simplify forming than a spread footing design would have. Pile foundations, furthermore, typically economize the amount of concrete and rebar necessary to cap the pile groups. As expected, the interior walls made up the heaviest proportion of building weight in the 18-story mass timber building design to shore up the lateral resistance and stiffness. For all concrete buildings, the floors were the heaviest assembly accounting for 61%, 44%, and 58% of total building weight for 8-, 12-, and 18-story buildings, respectively. The reason for the slightly lower percentage of floor weight in the 12-story building was the heavy foundation design (mat foundation), which skewed the percentage of total building weight.

Figure 4 displays the mass contribution from each type of material in all six building designs. Concrete was the most abundant material by mass in all concrete buildings, accounting for 92% to 94% of total building weight. In mass timber buildings, concrete was also the most abundant material (39% to 43%) followed by two mass timber products (20% to 32% for CLT and 6% to 8% for glulam). Because of the building code requirement, GWB was applied to the mass timber buildings, and amounts increased with the amount of stories. Therefore, the contribution increased 4%, 10%, and 15% of total building weight for 8, 12, and 18 stories, respectively. The embodied energy (EE) and embodied carbon (EC) for each building were determined by their manufacturing process and energy used in the process. The EE and EC for the whole building are determined by material quantities and the EE and EC for each individual material.

Building Material Life-Cycle Inventory

Life-cycle inventories for most building products are drawn from the DATASMART LCI Package (LTS 2021). DATASMART was developed to create a North American focused dataset from a combination of US LCI v.1.60 and Ecoinvent v 2.2 data. Concrete mix LCI datasets were drawn from the updated environmental product declarations (EPDs) developed by Athena Sustainable Materials Institute commissioned through the National Ready Mixed Concrete Association (NRMCA 2019b). Table 8 shows the LCIs chosen or developed for the material, electricity, and transportation fuel modeled in this study.

Although many mass timber products such as CLT are relatively new, glulam has been used in the United States for almost 100 years. The impacts of more recently developed mass timber products may be estimated from well-known production technologies and constitutive materials such as wood and adhesives (Stark and Cai 2021). The U.S. CLT manufacturing process data were collected for another project (Simonen and others 2019) but were analyzed and modified in this study for the U.S. Northeast region specifics, including wood species, eGrid profile, and transportation estimates. The most available softwood species in the Northeast region are eastern spruce (*Picea rubens* Sarg.) and eastern white pine (*Pinus strobus* L.). Thus, a mix of the two were used in the LCA model for the Northeast CLT product. The eGrid profile of the Northeast Power Coordinating Council (NPCC) was chosen for the Northeastern regional electricity model in the LCA (EPA 2022, 2023). Only road and rail transportation were considered because domestic and local sourcing of materials for CLT manufacturing was assumed. For distances shorter than 805 km, the materials were assumed to be transported by truck, whereas for distances longer than 805 km, a combination of truck (road) and train (rail) transport was assumed. These data and assumptions were used in SimaPro 9.1 to build the LCI of U.S. Northeast CLT and glulam. Table 9 gives the unit GWP impact of each material or product and the transportation modeled for the WBLCA in this study.

Life-Cycle Assessment Results

Tables A1 to A3 in the Appendix show the complete results (14 impact indicators) for the building life cycle of the Product and Construction stages including modules A1 to A5 of the three mass timber buildings and the three concrete buildings based on the functional unit (1 m^2 floor area). Figures A1 to A3 in the Appendix display the differences between the mass timber and concrete buildings for all these impact indicators. All three mass timber buildings outperformed the corresponding concrete buildings on nearly all environmental impact indicators except for primary energy consumption. Generally, all environmental impacts increased with increasing stories from 8 to 12 to 18. For instance, the GWP increased from 106 to 141 to 149 kg CO_2eq/m^2 floor area with increasing stories for the three mass timber buildings. However, the difference in GWP between the mass timber and concrete buildings with corresponding amounts of stories decreased from 50% to 47% to 28% as stories increased from 8 to 12 to 18, respectively. The mass timber buildings used significantly more renewable energy than the corresponding concrete buildings, an average of 11.8 times more. The total primary energy used, including the nonrenewable portion, in the mass timber buildings was 16% to 38% higher than in the corresponding concrete buildings.

The life-cycle stage that had the most environmental impact was the product stage (modules A1-A3), accounting for 85% to 95% of GWP for all mass timber and concrete

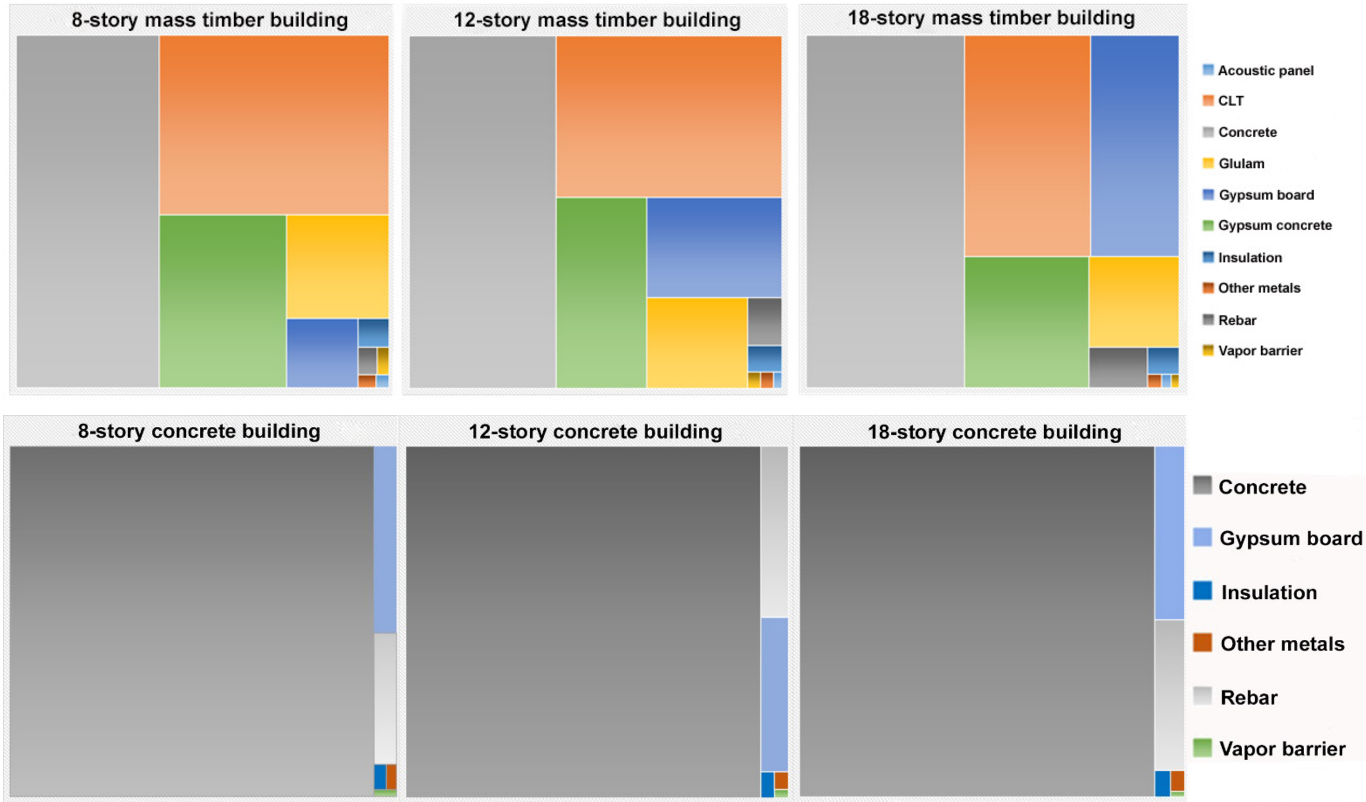

Figure 4—Building material distribution (measured by mass in kilograms) in each of the three mass timber buildings (top) and three concrete buildings (bottom) designed for the northeastern United States.

buildings. The transport module (A4) contributed only 1% of GWP in concrete buildings but 9% to 11% in mass timber buildings, mainly because of the assumption that primary materials such as concrete could be sourced locally within a short distance of 17 km, whereas the mass timber (CLT and glulam) was assumed to be sourced from a potential manufacturer in the state of Maine, with transportation distance to building site calculated as 460 km, 27 times farther than that for concrete. Domestically sourced mass timber products, assumed in this study, significantly lowered the GWP impact of mass timber buildings and improved their competitiveness. However, for current global mass timber product markets, domestically or locally sourced product may not be possible for many regions. This would only be likely to happen if the industry matures as it becomes more prevalent in construction and more wood species including hardwoods are used for CLT (APA 2020).

Contribution Analysis

Table 10 shows the contribution analysis of GWP from different building assemblies at the product stage (A1-A5). Floors, foundation, and walls were the three dominant contributors in all buildings. The largest GWP contributor in the 8-, 12-, and 18-story mass timber buildings were floors (47%), foundation (34%), and walls (59%), respectively.

The floors were the largest contributor to the total GWP of all concrete buildings, accounting for 52%, 36%, and 45% of total GWP for 8, 12, and 18 stories, respectively. The GWP impacts of all assemblies in the mass timber buildings were lower than those same assemblies in the corresponding concrete buildings, except the interior walls in the 18-story buildings. This anomaly was caused by the extra use of GWB required by the building code for high-rise mass timber buildings.

Table 11 and Figure 5 present the contribution analysis of GWP of different building materials for all the buildings. A comparison of the mass timber and concrete buildings is included for each amount of stories. Concrete and rebar were the two dominant contributors to all concrete buildings, accounting for 67% to 72% and 15% to 22% of total GWP from the product stage (modules A1-A5). In mass timber buildings, the two significant contributors to the GWP were mass timber (20%–37% for CLT and 5%–8% for glulam) and concrete (26%–32%). Because of the IBC 2021 building code requirement, GWB must be applied to all exposed mass timber, and this amount increased as the amount of stories increased from 8 to 12 to 18 stories. This resulted in an increasing contribution to GWP of 6% to 15% to 21% for 8, 12, and 18 stories, respectively. The total GWP of mass timber buildings was 50%, 52%, and 72% of

Table 8—Summary of the life-cycle inventory (LCI) source for all building materials, energy, and fuel modeled in the building designs

Material/energy/fuel	LCI process	Database/data source
Acoustic panel	Gypsum plaster board, at plant/US US-EI U	DATASMART (LTS 2021)
Aluminum stud	Galvanized steel sheet, at plant NREL/RNA U	DATASMART (LTS 2021)
Cross-laminated timber (CLT)	CLT	CORRIM[a] (Simonen and others 2019)
Concrete	Concrete, 3,000 lb/in^2[b]	NRMCA (2019a)
Concrete	Concrete, 4,000 lb/in^2	NRMCA (2019a)
Concrete	Concrete, 5,000 lb/in^2	NRMCA (2019a)
Construction energy	Diesel, combusted in industrial equipment NREL/US U	DATASMART (LTS 2021)
Electricity	Regional grids NPCC	DATASMART (LTS 2021)
Exterior brace framing	Hot rolled sheet, steel, at plant NREL/RNA U	DATASMART (LTS 2021)
Glulam	Glulam	CORRIM (Simonen and others 2019) and proxy processes
Gypsum concrete	Proxy process	DATASMART (LTS 2021)
Gypsum wallboard	Gypsum fiber board, at plant/US US-EI U	DATASMART (LTS 2021)
Insulation	Glass wool mat, at plant/US US-EI U	DATASMART (LTS 2021)
Insulation	Rock wool, packed, at plant/US US-EI U	DATASMART (LTS 2021)
Insulation	Polystyrene, extruded (XPS), at plant/US US-EI U	DATASMART (LTS 2021)
Polystyrene insulated sheathing	Polystyrene, extruded (XPS), at plant/US US-EI U	DATASMART (LTS 2021)
Rail transport	Transport, train, diesel powered NREL/US U	DATASMART (LTS 2021)
Rebar	Reinforcing steel, at plant/US US-EI U	DATASMART (LTS 2021)
Rectangular mullion: 3-5/8 in.[c] C stud	Galvanized steel sheet, at plant NREL/RNA U	DATASMART (LTS 2021)
Road transport	Transport, combination truck, diesel powered NREL/US U	DATASMART (LTS 2021)
Vapor barrier	Low density polyethylene resin, at plant NREL/RNA U	DATASMART (LTS 2021)

[a]Consortium for Research on Renewable Industrial Materials (Corvallis, Oregon, USA).
[b]1 lb/in^2 = 6.9 kPa.
[c]1 in. = 25.4 mm.

Table 9—Unit global warming potential (GWP) impact of each material and transportation used in this whole-building life-cycle assessment[a]

Material and transportation	Source	Unit	GWP ($kg\ CO_2eq$/one unit)
Aluminum, secondary, extruded NREL	DATASMART LCI package[b]	kg	3.11
CLT, proxy, NE	New dataset built with U.S. manufacture process	m^3	110.82
Concrete[c], 3,000 lb/in^2, EPD, NE	NRMCA (2019b)	yd^3	217.93
Concrete, 4,000 lb/in^2, EPD, NE	NRMCA (2019b)	yd^3	261.21
Concrete, 5,000 lb/in^2, EPD, NE	NRMCA (2019b)	yd^3	315.77
Galvanized steel sheet, at plant NREL/RNA U	DATASMART LCI package	kg	2.93
Glass wool mat, at plant/US* US-EI U	DATASMART LCI package	kg	2.95
Glulam, proxy, NE	New dataset built with U.S. manufacture process	m^3	81
Gypsum plaster board, at plant/US* US-EI U	DATASMART LCI package	kg	0.39
Gypsum wallboard product, type X, 0.625 in. (15.875 mm)/m^2/RNA	DATASMART LCI package	m^2	3.42
Low-density polyethylene resin, at plant NREL/RNA U	DATASMART LCI package	kg	2.19
Polystyrene, extruded, at plant/US-US-EI U	DATASMART LCI package	kg	11.3
Reinforcing steel, at plant/US-US-EI U	DATASMART LCI package	kg	1.56
Rock wool, packed, at plant/US* US-EI U	DATASMART LCI package	kg	1.35
Gypsum concrete, proxy	DATASMART LCI package	kg	0.07
Gypsum fiber board, at plant/US* US-EI U	DATASMART LCI package	kg	0.32
Transport, combination truck, diesel-powered NREL/US U	DATASMART LCI package	tkm	0.09
Transport, train, diesel-powered NREL/US U	DATASMART LCI package	tkm	0.02
Diesel, combusted in industrial equipment NREL/US U	DATASMART LCI package	L	3.23

[a]NREL, National Renewable Energy Laboratory; CLT, cross-laminated timber; NE, northeast; EPD, environmental product declaration; RNA, region North America; U, unit process; US-EI, U.S. ecoinvent; LCI, life-cycle inventory.
[b](LTS 2021).
[c]Conversions for concrete units: 1 lb/in^2 = 6.9 kPa, 1 yd^3 = 0.77 m^3.

Table 10—Product and construction stage global warming potential (GWP) contribution by assembly for mass timber and concrete multistory buildings

Building assembly	GWP contribution (kg CO_2eq/m^2)[a] Mass timber building	Concrete building	Difference (%)
8 stories			
Columns	8.42 (8%)	14.10 (7%)	–40
Exterior walls	5.08 (5%)	5.13 (2%)	–1
Floors	50.07 (47%)	111.97 (52%)	–55
Foundation	15.47 (15%)	27.66 (13%)	–44
Interior walls	27.31 (26%)	54.90 (26%)	–50
Total	106.35 (100%)	213.76 (100%)	–50
12 stories			
Columns	8.99 (6%)	27.29 (10%)	–67
Exterior walls	7.21 (5%)	7.32 (3%)	–1
Floors	31.19 (22%)	96.48 (36%)	–68
Foundation	47.52 (37%)	69.04 (26%)	–31
Interior walls	46.08 (33%)	66.92 (25%)	–31
Total	141.00 (100%)	267.04 (100%)	–47
18 stories			
Columns	7.92 (5%)	30.36 (15%)	–74
Exterior walls	6.83 (5%)	6.90 (3%)	–1
Floors	35.45 (24%)	94.09 (45%)	–62
Foundation	11.48 (8%)	15.32 (7%)	–25
Interior walls	87.39 (61%)	60.72 (29%)	44
Total	149.07 (100%)	207.39 (100%)	–28

[a]Percentage of total GWP contribution for each assembly shown in parentheses.

the total GWP of the corresponding concrete buildings, as shown side by side in Figure 5.

Carbon Storage

Mass timber buildings can store carbon for the building's entire lifespan, which can potentially mitigate climate change. In this case study, the total wood carbon stored in the mass timber buildings ranged from 3,187 to 6,625 t CO_2eq in the whole building, or 311 to 365 kg CO_2eq per m^2 floor area, as shown in Table 12.

For each of the three mass timber buildings, percentages of carbon stored in different assemblies are shown in Figure 6. Floors stored the most carbon, and walls stored the second-most amount of carbon. In building designs, clients could opt for CLT decks instead of steel framing, which could further sequester carbon in the building.

Discussion and Conclusions

In this WBLCA study, a significant decrease in total GWP in the product stage (A1-A3) was achieved by replacing concrete and steel with mass timber products. Three pairs of mass timber and concrete buildings were designed with functional equivalency for comparative LCA analysis and were based on the IBC 2021 building code and geological features. The total GWP reductions in mass timber buildings were 50% for the 8-story building, 47% for the 12-story building, and 28% for the 18-story building compared with their functionally equivalent concrete buildings. For 18-story building, further reductions might be possible with technologies that permit less GWB encapsulation and advanced lateral force restating systems that perform with the equivalent stiffness of reinforced concrete. Most of the reductions primarily resulted from the use of CLT and glulam, which substituted 67% to 79% of concrete and 62% to 91% of rebar use in the corresponding concrete building designs. Impacts from the product stage (module A1 to A3) played a major influence on the total GWP in the current case study. Assumptions were made for the transportation module (A4) and the construction module (A5) because of the limited practical data available for those modules. When more practical data are available for those modules, the corresponding results can be updated. The competitiveness of mass timber materials is expected to improve as mass timber production becomes more prevalent throughout North America.

In addition to the GWP impact, 13 other impact indicators were also assessed (see Tables A1–A3 and Figs. A1–A3 in the Appendix). All three mass timber buildings outperformed the corresponding concrete buildings on nearly all environmental impact indicators except for primary energy consumption. Generally, all environmental impacts increased with increasing amounts of stories from 8 to 12 to 18. For instance, the GWP of the mass timber buildings increased from 106 to 141 to 149 kg CO_2eq/m^2 floor area for 8, 12, and 18 stories, respectively. The design of the floor and interior wall assemblies played an important role in the GWP reported in the three mass timber buildings. Foundation design also was a significant contributor if the

Table 11—Product stage global warming potential (GWP) contribution by building material for mass timber and concrete multistory buildings

Building material	GWP contribution (kg CO_2eq/m^2)[a] Mass timber building	Concrete building	Difference (%)
8 stories			
Acoustic panel	0.26 (0.2%)	— (—)	—
CLT	39.81 (37.4%)	— (—)	—
Concrete	30.47 (28.6%)	154.78 (72%)	–80
Glulam	8.42 (7.9%)	— (—)	—
Gypsum board	6.34 (6.0%)	10.62 (5%)	–40
Gypsum concrete	8.57 (8.1%)	— (—)	—
Insulation	4.43 (4.2%)	8.26 (4%)	–46
Other metals	2.53 (2.4%)	5.34 (2%)	–53
Rebar	2.97 (2.8%)	32.23 (15%)	–91
Vapor barrier	2.55 (2.4%)	2.53 (1%)	1
Total	106.35 (100%)	213.76 (100%)	–50
12 stories			
Acoustic panel	0.26 (0.2%)	— (—)	—
CLT	43.67 (31%)	— (—)	—
Concrete	36.16 (26%)	178.14 (67%)	–80
Glulam	8.99 (6%)	— (—)	—
Gypsum board	21.60 (15%)	12.23 (5%)	77
Gypsum concrete	8.47 (6%)	— (—)	—
Insulation	5.61 (4%)	10.57 (4%)	–47
Other metals	2.75 (2%)	5.75 (2%)	–52
Rebar	11.36 (8%)	58.20 (22%)	–80
Vapor barrier	2.13 (2%)	2.14 (1%)	0
Total	141.00 (100%)	267.04 (100%)	–47
18 stories			
Acoustic panel	0.24 (0.2%)	— (—)	—
CLT	33.08 (22%)	— (—)	—
Concrete	44.44 (30%)	138.10 (67%)	–68
Glulam	7.92 (5.3%)	— (—)	—
Gypsum board	30.78 (21%)	11.24 (5%)	174
Gypsum concrete	7.92 (5.3%)	— (—)	—
Insulation	5.20 (3.5%)	9.81 (5%)	–47
Other metals	2.52 (1.7%)	5.26 (3%)	–52
Rebar	15.93 (11%)	41.94 (20%)	–62
Vapor barrier	1.03 (0.7%)	1.04 (1%)	–1
Total	149.07 (100%)	207.39 (100%)	–28

[a]Percentage of total GWP contribution for each assembly shown in parentheses.

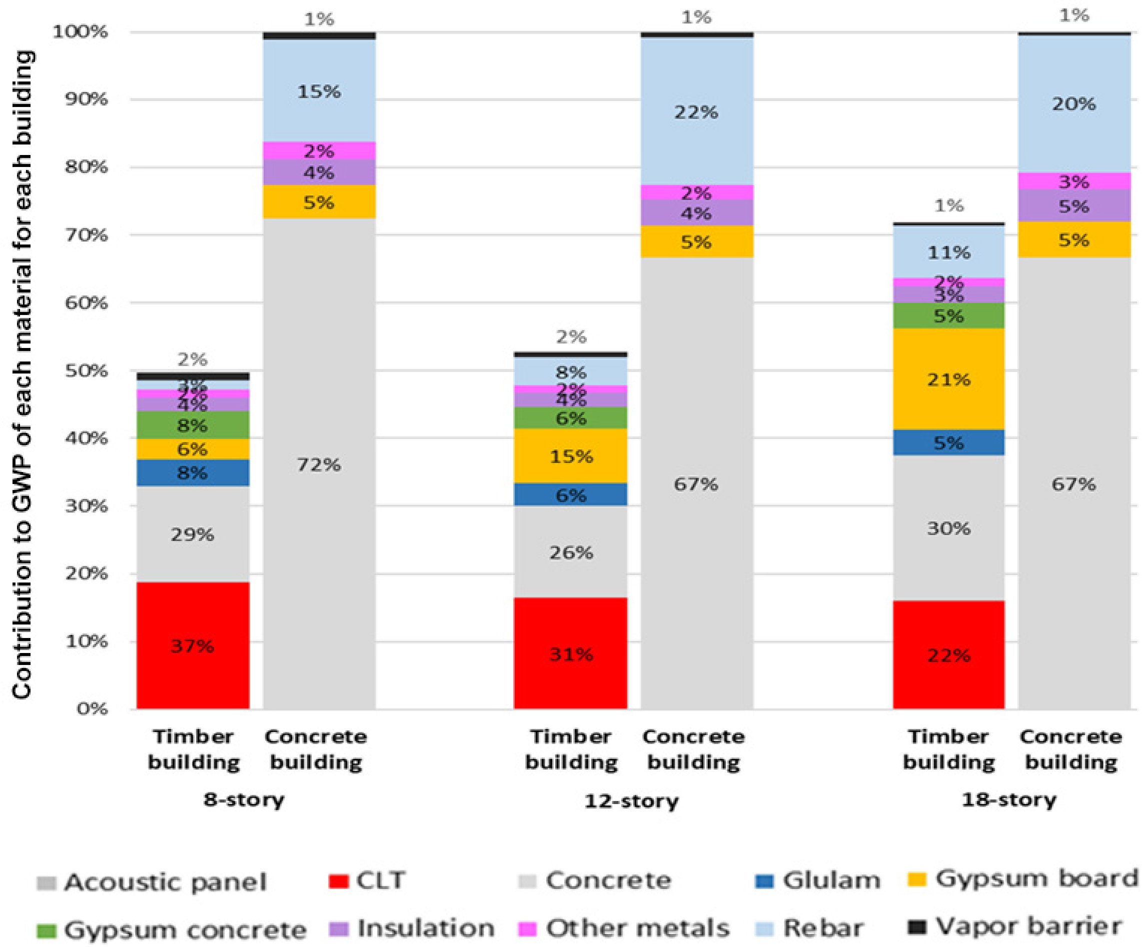

Figure 5—Contribution of building materials to the total global warming potential (GWP) from the Product stage of the three mass timber buildings and three corresponding concrete buildings.

Table 12—Total wood carbon stored in the three mass timber buildings

Total stories	Residential stories	Office–commercial stories	Total floor area (m^2 (ft^2))	Total CO_2eq in wood (t)	Total CO_2eq in wood/area (kg CO_2eq/m^2 (kg CO_2eq/ft^2))
8	6	2	9,476 (102,000)	3,187	336 (31.2)
12	8	4	14,214 (153,000)	5,191	365 (33.9)
18	8	10	21,321 (229,500)	6,625	311 (28.9)

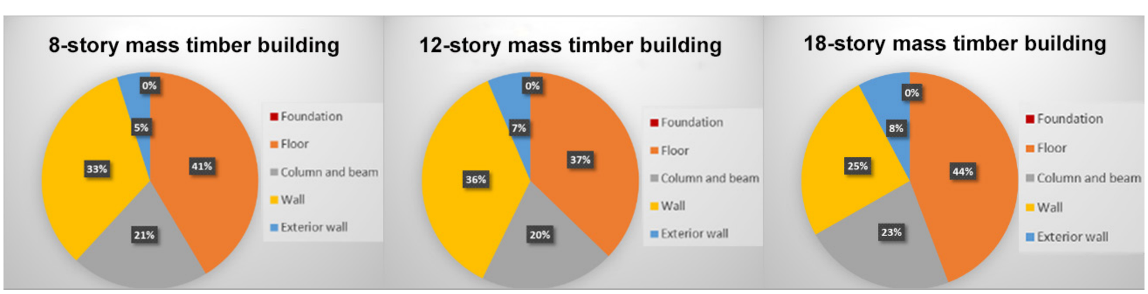

Figure 6—Percentage carbon storage in each building assembly of the three mass timber buildings.

type of foundation required a substantial amount of concrete, such as the mat footing design.

More carbon could be stored in mass timber buildings with the use of certain wood species, for example, southern yellow pine. In this study, with eastern spruce used in the mass timber materials, about 311 to 365 kg CO_2eq per m^2 floor area were stored in the buildings. The buildings were designed for the Northeastern U.S. region with mass timber products assumed to be manufactured in the same region with the available and abundant wood species of eastern spruce.

Prospective

According to UNEP (2018), 11% of the building sector's CO_2eq emissions (40% of total global CO_2eq emissions) are from materials and construction. The use of mass timber in the building sector provides opportunities to reduce global CO_2 emissions and mitigate climate change for future generations. However, opportunities and challenges co-exist. Mass timber use in buildings for environmental benefit is also challenged by sustainable management of forests at national and international levels to prevent deforestation (Brashaw and Bergman 2021). Building longevity and mass timber recycle–reuse rate at the end of building service life are also influencing the carbon sequestration effect and delaying the global warming emergency. In summary, the mass timber building industry revolution will hugely contribute to not only global sustainability but also green economic development.

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The manuscript was reviewed by the following experts in the field:

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Appendix—Life-Cycle Environmental Impacts of Mass Timber and Concrete Buildings

The following tables and figures show the life-cycle environmental impacts of the whole mass timber and concrete buildings by amount of stories and for the product stage (A1-A5). Impacts are shown for each indicator. The figures show the impacts of the mass timber buildings in percentage as a comparison with the corresponding concrete building. Impacts again are shown for each indicator.

Table A1—Life-cycle impacts (per square meter of floor area) of the 8-story mass timber and concrete buildings for the product stage[a]

			A1-A3			A4			A5			Total		
LCIA indicator	Abbreviation	Unit	Mass timber building	Concrete building	Difference (%)	Mass timber building	Concrete building	Difference (%)	Mass timber building	Concrete building	Difference (%)	Mass timber building	Concrete building	Difference (%)
Global warming potential, biogenic	GWP	kg CO_2eq	—	—	—	—	—	—	—	—	—	—	—	—
Global warming potential, fossil	GWP	kg CO_2eq	90.66	203.66	–55	11.96	2.71	341	3.73	7.39	–49	106.35	213.76	–50
Depletion potential of the stratospheric ozone layer	ODP	kg CFC11eq	7.66E–06	4.42E–05	–83	2.10E–08	4.77E–09	341	7.10E–09	1.40E–08	–49	7.68E–06	4.42E–05	–83
Acidification potential of soil and water sources	AP	kg SO_2eq	0.40	0.71	–44	0.07	0.02	331	0.05	0.10	–49	0.51	0.83	–38
Eutrophication potential	EP	kg Neq	0.14	0.31	–55	6.29E–03	1.45E–03	334	3.81E–03	7.55E–03	–49	0.15	0.32	–53
Formation potential of tropospheric ozone	SFP	kg O_3eq	8.65	13.11	–34	1.91	0.45	328	1.60	3.16	–49	12.15	16.71	–27
Abiotic depletion potential for fossil resources	ADPf	MJ, NCV	1,021.90	1,515.59	–33	149.63	33.93	341	50.38	99.71	–49	1,221.91	1,649.23	–26
Abiotic depletion potential (elements)	ADPe	kg Sbe	9.19E–05	1.70E–04	–46	5.43E–07	1.23E–07	341	1.83E–07	3.62E–07	–49	9.26E–05	1.71E–04	–46
Fossil fuel depletion	FFD	MJ surplus	132.45	138.62	–4	22.47	5.09	341	7.56	14.96	–49	162.48	158.68	2
Renewable primary energy carrier used as energy	RPRE	MJ, NCV	799.43	57.26	1,296	0.34	0.08	341	0.12	0.23	–49	799.89	57.57	1,290
Nonrenewable primary energy carrier used as energy	NRPRE	MJ, NCV	1448.36	1,816.32	–20	151.82	34.42	341	51.14	101.22	–49	1,651.32	1,951.96	–15
Consumption of freshwater resources	FW	m^3	0.82	2.30	–64	1.33E–03	3.01E–04	341	4.48E–04	8.86E–04	–49	0.83	2.30	–64
Calcination or carbonation emissions	CCE	kg CO_2eq	11.60	59.40	–80	—	—	—	—	—	—	11.60	59.40	–80
Hazardous waste disposed	HWD	kg	0.03	0.08	–65	9.56E–05	2.17E–05	341	3.22E–05	6.38E–05	–49	0.03	0.08	–65
Nonhazardous waste disposed	NHWD	kg	30.34	86.59	–65	1.07	0.24	341	0.36	0.72	–49	31.78	87.55	–64

[a]LCIA, life-cycle inventory analysis; CFC, chlorofluorocarbon; NCV, net calorific value; Sbe, antimony element.

Table A2—Life-cycle impacts (per square meter of floor area) of 12-story mass timber and concrete buildings for the product stage[a]

			A1-A3			A4			A5			Total		
LCIA indicator	Abbreviation	Unit	Mass timber building	Concrete building	Difference (%)	Mass timber building	Concrete building	Difference (%)	Mass timber building	Concrete building	Difference (%)	Mass timber building	Concrete building	Difference (%)
Global warming potential, biogenic	GWP	kg CO_2eq	—	—	—	—	—	—	—	—	—	—	—	—
Global warming potential, fossil	GWP	kg CO_2eq	121.42	254.03	–52	14.23	3.14	353	5.35	9.86	–46	141.00	267.04	–47
Depletion potential of the stratospheric ozone layer	ODP	kg CFC11eq	1.03E–05	6.22E–05	–83	2.50E–08	5.53E–09	353	1.02E–08	1.87E–08	–46	1.03E–05	6.22E–05	–83
Acidification potential of soil and water sources	AP	kg SO_2eq	0.53	0.89	–41	0.08	0.02	343	0.07	0.13	–46	0.68	1.04	–35
Eutrophication potential	EP	kg Neq	0.20	0.43	–54	0.01	0.00	346	5.46E–03	1.01E–02	–46	0.21	0.44	–52
Formation potential of tropospheric ozone	SFP	kg O_3eq	10.90	15.98	–32	2.27	0.52	341	2.28	4.21	–46	15.46	20.71	–25
Abiotic depletion potential for fossil resources	ADPf	MJ, NCV	1,381.82	1,987.31	–30	178.00	39.29	353	72.15	133.07	–46	1,631.97	2,159.67	–24
Abiotic depletion potential (elements)	ADPe	kg Sbe	1.21E–04	2.10E–04	–42	6.47E–07	1.43E–07	353	2.62E–07	4.83E–07	–46	1.22E–04	2.10E–04	–42
Fossil fuel depletion	FFD	MJ surplus	172.44	172.57	0	26.73	5.90	353	10.83	19.97	–46	209.99	198.44	6
Renewable primary energy carrier used as energy	RPRE	MJ, NCV	874.83	71.91	1117	0.41	0.09	353	0.17	0.31	–45.783	875.41	72.30	1,111
Nonrenewable primary energy carrier used as energy	NRPRE	MJ, NCV	1,877.69	2,355.33	–20	180.60	39.87	353	73.24	135.09	–45.783	2,131.53	2,530.29	–16
Consumption of freshwater resources	FW	m^3	1.11	2.84	–61	1.58E–03	3.49E–04	353	6.41E–04	1.18E–03	–45.783	1.12	2.84	–61
Calcination or carbonation emissions	CCE	kg CO_2eq	13.48	67.95	–80	—	—	—	—	—	—	13.48	67.95	–80
Hazardous waste disposed	HWD	kg	0.04	0.10	–61	1.14E–04	2.51E–05	353	4.61E–05	8.51E–05	–45.783	0.04	0.10	–60

[a]LCIA, life-cycle inventory analysis; CFC, chlorofluorocarbon; NCV, net calorific value; Sbe, antimony element.

Table A3—Life-cycle impacts (per square meter of floor area) of 18-story mass timber and concrete buildings for the product stage[a]

			A1-A3			A4			A5			Total		
LCIA indicator	Abbreviation	Unit	Mass timber building	Concrete building	Difference (%)	Mass timber building	Concrete building	Difference (%)	Mass timber building	Concrete building	Difference (%)	Mass timber building	Concrete building	Difference (%)
Global warming potential, biogenic	GWP	kg CO_2eq	—	—	—	—	—	—	—	—	—	—	—	—
Global warming potential, fossil	GWP	kg CO_2eq	129.99	196.26	–34	13.01	2.55	410	6.07	8.58	–29.285	149.07	207.39	–28
Depletion potential of the stratospheric ozone layer	ODP	kg CFC11eq	1.02E–05	5.73E–05	–82	2.29E–08	4.49E–09	410	1.15E–08	1.63E–08	–29.285	1.02E–05	5.73E–05	–82
Acidification potential of soil and water sources	AP	kg SO_2eq	0.54	0.69	–22	0.07	0.01	397	0.08	0.11	–29.285	0.69	0.82	–15
Eutrophication potential	EP	kg Neq	0.21	0.32	–34	0.01	0.00	401	6.20E–03	8.77E–03	–29.285	0.23	0.33	–32
Formation potential of tropospheric ozone	SFP	kg O_3eq	10.77	12.30	–12	2.08	0.42	394	2.59	3.67	–29.285	15.44	16.39	–6
Abiotic depletion potential for fossil resources	ADPf	MJ, NCV	1,397.21	1,522.43	–8	162.77	31.93	410	81.89	115.81	–29.285	1,641.87	1,670.17	–2
Abiotic depletion potential (elements)	ADPe	kg Sbe	1.23E–04	1.62E–04	–24	5.91E–07	1.16E–07	410	2.97E–07	4.21E–07	–29.285	1.24E–04	1.62E–04	–24
Fossil fuel depletion	FFD	MJ surplus	166.02	132.80	25	24.44	4.79	410	12.29	17.38	–29.285	202.75	154.98	31
Renewable primary energy carrier used as energy	RPRE	MJ, NCV	697.63	55.92	1,148	0.37	0.07	410	0.19	0.27	–29.285	698.19	56.26	1,141
Nonrenewable primary energy carrier used as energy	NRPRE	MJ, NCV	1,828.69	1,805.91	1	165.14	32.40	410	83.13	117.56	–29.285	2076.97	1,955.87	6
Consumption of freshwater resources	FW	m^3	1.22	2.17	–44	1.44E–03	2.83E–04	410	7.27E–04	1.03E–03	–29.285	1.22	2.17	–44
Calcination or carbonation emissions	CCE	kg CO_2eq	16.85	52.50	–68	—	—	—	—	—	—	16.85	52.50	–68
Hazardous waste disposed	HWD	kg	0.04	0.08	–46	1.04E–04	2.04E–05	410	5.24E–05	7.41E–05	–29	0.04	0.08	–46

[a]LCIA, life-cycle inventory analysis; CFC, chlorofluorocarbon; NCV, net calorific value; Sbe, antimony element.

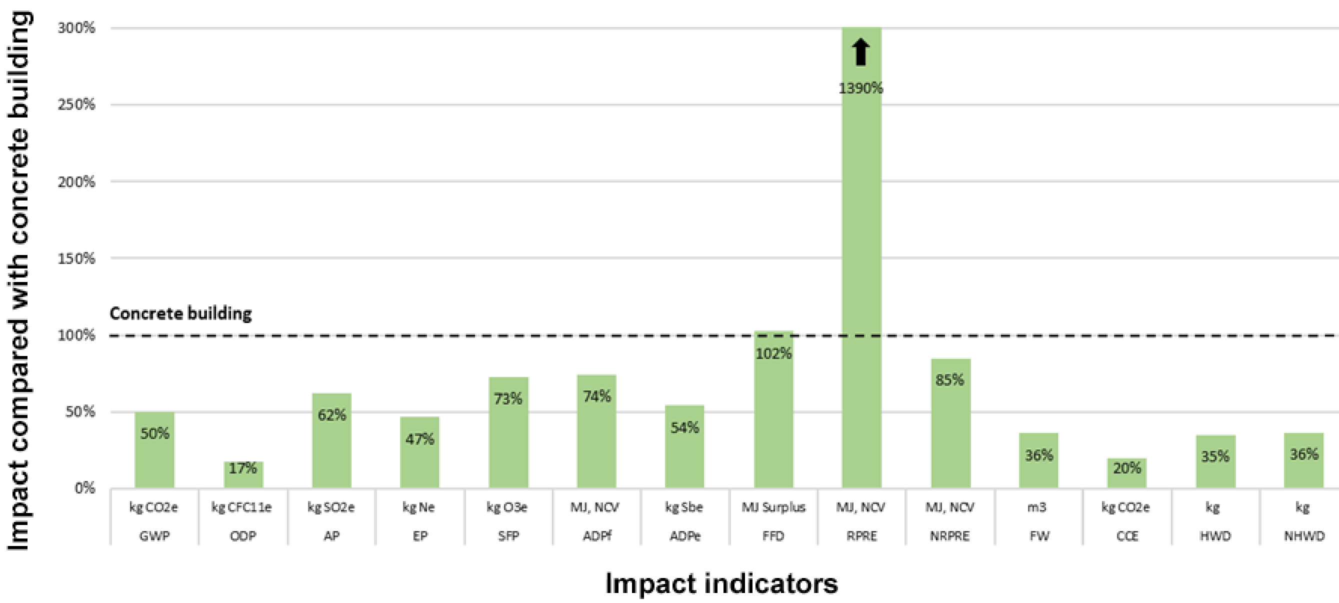

Figure A1—Life-cycle assessment environmental impacts of the 8-story mass timber building from the product stage (A1-A5) as percentage compared with equivalent concrete building.

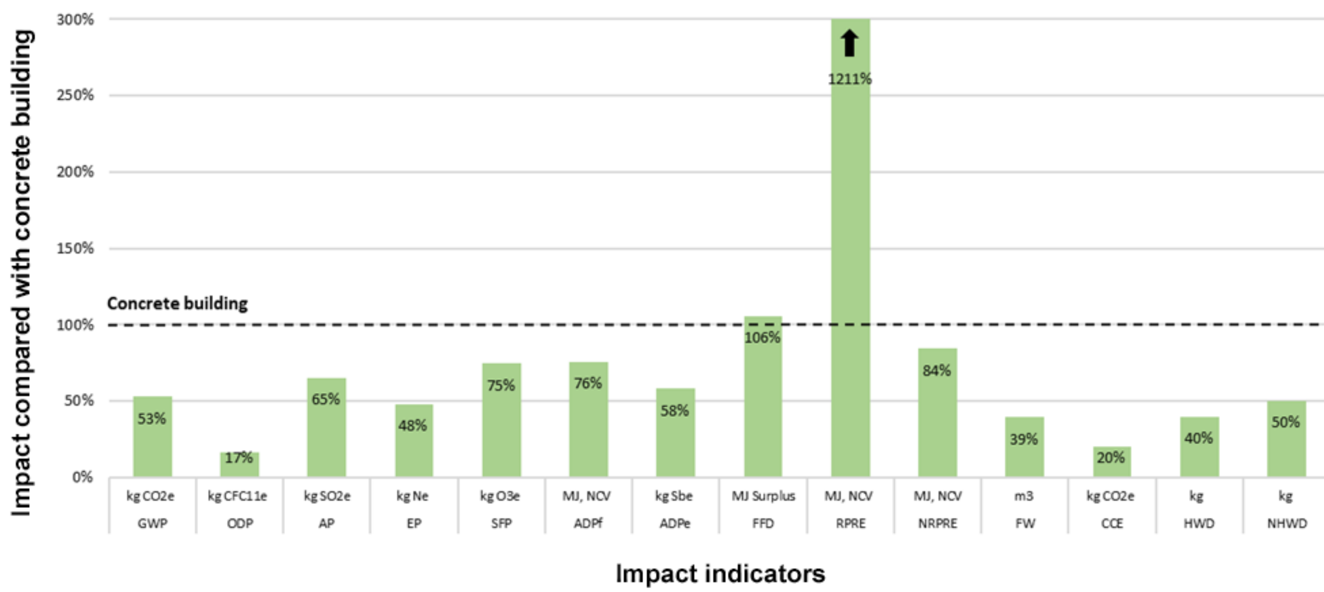

Figure A2—Life-cycle assessment environmental impacts of the 12-story mass timber building from the product stage (A1-A5) as percentage compared with equivalent concrete building.

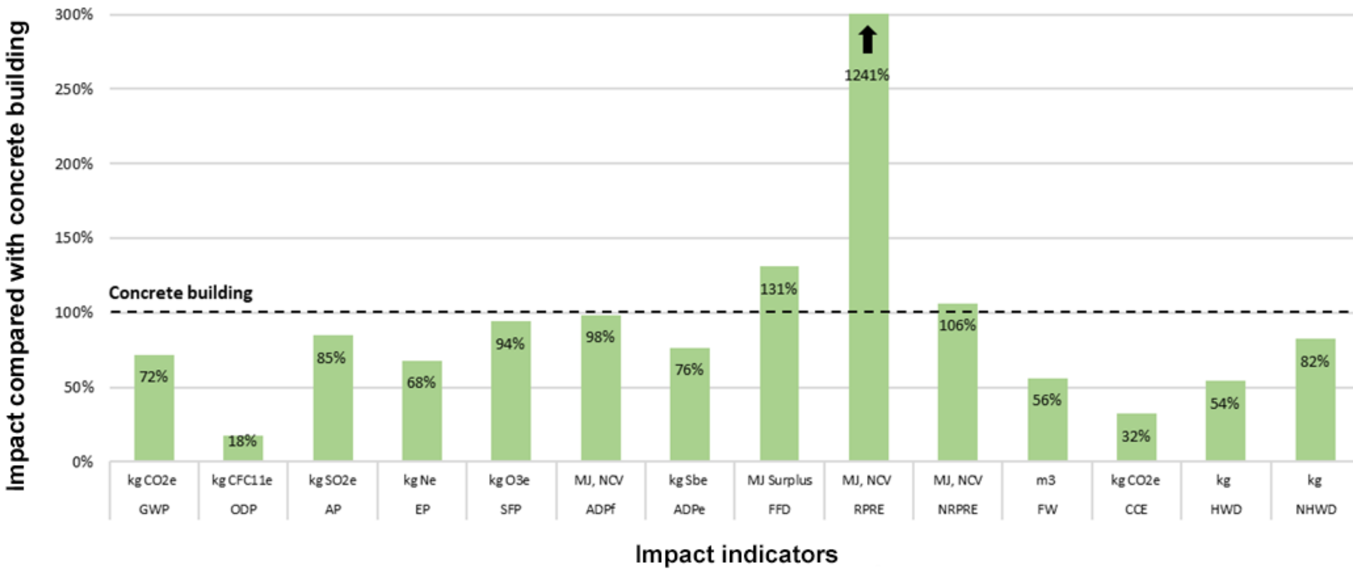

Figure A3—Life-cycle assessment environmental impacts of the 18-story mass timber building from the product stage (A1-A5) as percentage compared with equivalent concrete building.