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Chapter

Carbon Impacts of Engineered Wood Products in Construction

Hongmei Gu, Prakash Nepal, Matthew Arvanitis and Delton Alderman

Abstract

Buildings and the construction sector together account for about 39% of the global energy-related CO_2 emissions. Recent building designs are introducing promising new mass timber products that have the capacity to partially replace concrete and steel in traditional buildings. The inherently lower environmental impacts of engineered wood products for construction are seen as one of the key strategies to mitigate climate change through their increased use in the construction sector. This chapter synthesizes the estimated carbon benefits of using engineered wood products and mass timber in the construction sector based on insights obtained from recent Life Cycle Assessment studies in the topic area of reduced carbon emissions and carbon sequestration/storage.

Keywords: life cycle assessment, mass timber products, forest carbon, wood products carbon, carbon sequestration/storage, avoided emissions

1. Introduction

Wood utilization in construction is a practice as old as human civilization. Value-added wood products harvested from forests have been used as building materials for millennia. With global forest resources strained, research in efficient use of harvested wood materials with engineered conceptions has increased significantly in recent years. Traditional wood building products, such as plywood, oriented strandboard (OSB) and I-Joists, are now complemented by emerging mass timber products, such as Cross Laminated Timber (CLT) [1], Glue Laminated Timber (GLULAM), Nail Laminated Timber (NLT), Dowel Laminated Timber (DLT), and Mass Ply Panels (MPP). These products are all engineered for widespread and efficient use in construction.

Mass timber is a term used to describe innovative wood product systems that utilize large, solid wood panels for wall, floor, and roof construction. These panels are six feet or more in width and length, and are manufactured with resin, nails, or by the use of dowels. Each layer of boards is oriented perpendicular to the adjacent layer and dowelled, glued, or nailed on the wide face of each board, in a symmetric manner in order that the outer layers have the same orientation. Panels can be used in CLT, DLT, GLULAM, NLT, and MPP systems. Mass timber products can be used to build traditional houses, office buildings, and high-rise structures.

Mass timber use is increasing around the world not only because of the desirable properties of engineered designs, but also due to their low-carbon footprint and carbon storage benefits. In addition, mass timber products are renewable materials; carbon loss in forests due to increased harvests suggest the need for the manufacture of mass timber products, which can offset carbon loss over time as forest biomass regrowth occurs on forestland. Until recently the use of wood in high-rise buildings had been limited due to building code restrictions. A recent change in the International Building Code now allows for mass timber use in buildings up to 18 stories. Sustainability of the mass timber buildings has been studied since the first USDA-FS Tall Wood Building competition winner “Framework” (**Figure 1**) building was designed, and progresses with the current “Ascent” building, to-be-the-tallest mass timber building (**Figure 2**) in the North America. Research and code development have paved the way for architects and building developers who are increasingly turning to mass timber building designs for both new construction and renovations. One of their aspirations is to help achieve the UN Climate Change Paris Agreement [2] goal of limiting global warming to no more than 1.5°C temperature rise from pre-industrial times. Given that the building sector accounts for 39% [3] of total global warming potential (GWP), researchers have conducted systematic assessment on whole-building environmental impacts for potential GWP reductions, using an internationally accepted method called Life Cycle Assessment (LCA) [4].

LCA is a holistic and scientific method for assessing environmental impacts from all life cycle stages of a product, process, service, or even a whole-building system. International standards ISO 14040 [5] and ISO 14044 [6] provide guidelines, principles, and framework to conduct an LCA. Standards such as ISO 21930 (2017) [7] and EN 15978 (2011) [8] provide guidelines for assessing whole-building system environmental performance over the entire building life cycle.

Environmental impacts of engineered wood products and mass timber use in construction can be evaluated within two LCA frameworks. An attributional LCA evaluates environmental impacts of manufacturing, installation, use, and disposal of a product (9–10). In contrast, a consequential LCA evaluates change in environmental impacts due to a change in product output or a change in a service

Figure 1.
12-story framework building with mass timber from ground floor (not built) designed for Portland Oregon US (Credit: Lever Architecture).

Figure 2.
25-story Ascent building built with mass timber products in Milwaukee Wisconsin US (Credit: Thornton Tomasetti and Korb & associates).

or a system [9–11]. In the case of wood products LCA, an attributional LCA, for example, provides information about the amount of GHG released during manufacturing of a unit (m^3) of lumber or CLT. In contrast, a consequential LCA evaluates overall greenhouse gas (GHG) emission, of increased demand for lumber or CLT use in buildings, including both direct (within system boundary) and indirect (e.g., change in forest land use) effects resulting from such increased demand.

Engineered wood products (EWP) used in buildings have a long history. Glulam timber was used to construct an auditorium in Basel Switzerland [12], and plywood became a popular engineered wood building material in the early 1900's, followed by OSB and Laminated Veneer Lumber (LVL) invented in the mid 1960's. In the mid-1970's, CLT was first used as a building material in a roof system. Now, with architects and developers aiming to achieve more sustainable designs, mass timber products such as NLT, DLT, and MPPs are becoming more and more popular.

With the Tall Wood building movement in North America ramping up [13–15], the environmental benefits of using mass timber and other engineered wood products have been scientifically examined in multiple studies around the world, and consider global forest resource availability and depletion, and the impact on world forest regeneration and protection. This chapter highlights carbon reduction and the storage benefits of engineered and mass timber products utilizing insights obtained from recent LCA studies.

2. Forest carbon, harvested wood products carbon, and avoided carbon emissions of substituting wood for non-wood materials in the construction sector

Increased demand for wood used in the construction sector may lead to changes in timber growth, growing stock inventory, and harvest that affect the storage of forest carbon. It may also alter the quantity of wood products manufactured and used to displace non-wood materials affecting carbon stored in wood products and avoided manufacturing emissions. Potential increased timber prices resulting from increased demand may encourage increased investment and forest management activities contributing to higher forest growth, growing stock, and reforestation (and forest carbon). Price increases might also lead to unsustainable harvesting in a region that supplies wood to wood-consuming industries. All of these potential effects should be considered when evaluating the overall carbon benefit of substituting wood for non-wood materials in construction. A consequential LCA provides a framework to consider all potential changes over a given time frame; the projected environmental effects for increased wood demand scenarios are compared with the effects projected for the business-as-usual reference case. The difference between the two scenarios constitutes the net emissions effects of increased wood use in the construction sector.

Using a consequential LCA, Nepal et al. [16] evaluated a scenario of increased softwood lumber and structural panel use in nonresidential construction in the United States, compared to a reference scenario without such an increase in wood consumption. They found that for each ton of CO_2e (tCO_2e) in additional wood consumption that replaced non-wood material in nonresidential construction in the United States, there was a net savings of 2.33 tCO_2e emissions over a period of 50 years. This estimate considered changes in carbon storage in forests (including logging residues) due to biological regrowth and market induced investment in forest management, the carbon stored in harvested wood products, and manufacturing emissions. In another study, Hildebrandt et al. [17] evaluated various scenarios of increases in annual demand for CLT-based solid wood structures and the Glulam-based frame structures in Europe by 2030. Their results indicated that these structures would result in lower annual GHG emissions and higher carbon stored in wood products (used in buildings), with an estimated combined annual carbon benefit of about 29.6 to 60.5 million tCO_2e per year during the 2015–2030 time-frame. The results were dependent upon the assumed future increases in the growth rates of different wood products used for construction. The derived combined carbon benefit per unit of CO_2 in additional wood consumed, given their projected changes in carbon stored in the wood products used in housing stock during the same period (11.8 to 15.4 million tCO_2e per year), was 2.50 to 3.93 tCO_2e/tCO_2e. The changes in forest biomass carbon that would result from increased harvests was not considered in these estimates, which may increase or decrease the derived avoided emissions depending on how forest management would change in response to increased timber harvests in Europe. Similarly, Smyth et al. [18] estimated the avoided emissions benefits of wood substitution in a built environment in Canada that included single-family and multi-family housing, six-story multiuse buildings, residential flooring, furniture, and decking reported an average avoided emissions benefit of 0.54 tCO_2e/tCO_2e for sawnwood and 0.45 tCO_2e/tCO_2e for plywood. Their estimate is based on a potential increase in wood use in those structures and excludes changes in forest ecosystem carbon and carbon stored in harvested wood products.

Findings from these studies indicate that there are considerable variabilities and uncertainty in the estimated GHG reduction benefits of wood products substitution in buildings. This is mainly due to the differences in the system boundary (e.g., consideration of direct or market induced effects on forest carbon), non-wood materials substituted (steel vs. concrete), energy mix assumed to be used in manufacturing wood products (e.g., wood energy and fossil energy), and types of buildings analyzed (low-rise vs. high-rise, single-family vs. multi-family, residential vs. nonresidential, etc.), and whether carbon storage in wood products is considered. This suggests that the carbon benefits of wood substitution in the construction sector should be evaluated holistically, considering all potential direct and indirect effects (e.g., land use change) caused by increased wood consumption in the building sector.

3. Carbon emission reductions with engineered wood products and mass timber use in the building sector

A whole building LCA (WBLCA) is typically performed to evaluate the total environmental performance of a building from materials utilized and operation during their entire life cycle. Consistent with International Standards [7–8], the system boundary of a WBLCA (**Figure 3**) starts with the product manufacturing stage (stage A1-A3), followed by construction (A4-A5), use (B1-B7) and the end of life (C1-C4) process. Environmental benefits or burdens after the end of life of a building are typically considered beyond the system boundary and depend on whether building materials, after demolition, are reused, recycled to produce new products, burned with or without energy capture, or dumped in landfills.

Buildings constructed with a large quantity of EWPs are usually compared to traditional concrete and steel buildings in order to examine the materials impact on the whole-building life cycle environmental performance. **Table 1** summarizes the embodied carbon of select building materials as a comparison. Concrete and steel, the main building materials used in traditional buildings, are carbon intensive materials. In contrast, EWPs are low-carbon impact materials. Therefore, CLT and other mass timber products use are emerging into the building sector

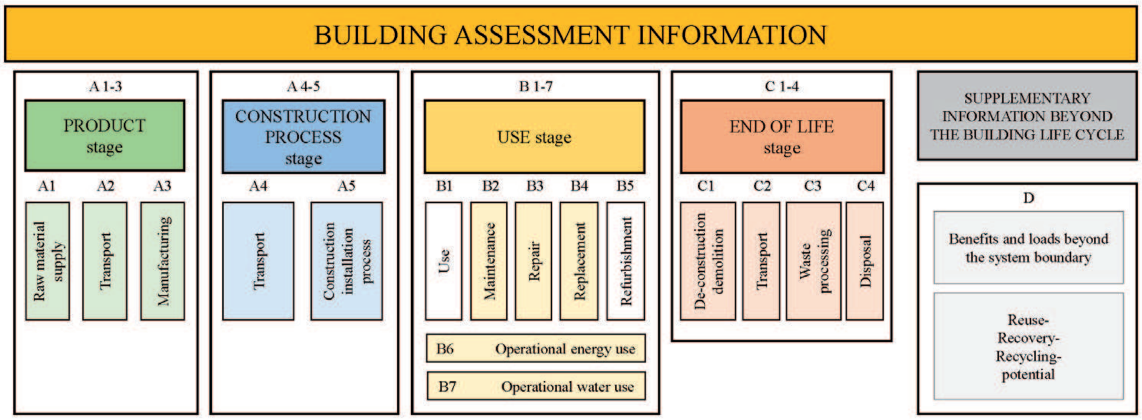

Figure 3.
Building life cycle stages and modules for building life cycle assessment.

Building Material	**GWP**[1]
1 m^3	kg CO$_2$ eq
Concrete[2]	225~550
Galvanized steel sheet	2929
Cross Laminated Timber (North America)	110~158
Glue Laminated Timber (North America)	81~515
Laminated Veneer Lumber	423
Plywood	368
Oriented Strand Board	361
Wood I-Joist[3]	17

[1] *Global warming potential from US LCI database or North American EPD.*
[2] *Concrete mix between 2500 psi~5000 psi, and values are from National Ready Mixed Concrete Association report.*
[3] *From American Wood Council EPD for 10 meter long I-Joist.*

Table 1.
Common building materials carbon emissions from product stage (A1-A3 in **Figure 1***).*

to replace some portion of concrete and steel use in mid-to-high rise residential buildings [14–15]. I-joists, used as EWPs in construction, are typically used in floor and roof framing, due to their extremely high-strength relative to their mass (or volume), thus they are assessed in LCA with length as their functional unit rather than volume.

Comparative building LCA is often applied to assess the total carbon emission difference between traditional concrete buildings and buildings with mass timber or other engineered wood products under the assumption of functional equivalency. A significant reduction in carbon emissions or global warming potential from mass timber buildings, has been discovered as a result of several whole-building LCA comparative studies [19–23]. Embodied carbon (EC) refers to the building's total upfront carbon emissions from the manufacture of all materials, transportation, and installation of construction materials. EC does not include the carbon stored in materials, or of the impact from building operational energy. EC, from building life cycle Stage A (module A1 to A5), was reported to drop by between 18% and 50% for mid-to-high rise mass timber buildings as compared to traditionally-built concrete and steel counterparts, depending on the amount of EWPs used in the buildings. If 384 $kgCO_{2e}/m^2$ of floor area is assumed as a median value for EC (for traditional concrete and steel buildings), as suggested in Simone et al. [23], then with an 18–50% reduction from mass timber used to replace concrete and steel, the mass timber buildings EC would be between 157 to 315 $kgCO_{2e}/m^2$ of floor area. Globally 230 billion m^2 [24] of total floor area is projected to be built by 2060 in order to meet projected world urban population growth demand, a reduction of about 16 to 44 billion tonnes CO_2e emissions may be achieved with the construction of mass timber EWP buildings rather than with concrete and steel materials. For perspective, CO_2 emissions reduction of this magnitude would be equivalent to the removal of 3.5 to 9.6 billion passenger vehicles from the road in one year (*4.6 metric tons* CO_{2eq}*/vehicle/year quoted from EPA's GHG equivalencies Calculator* [25]), or reducing electricity use by 22 to 62 trillion kWh (*7.09 ×* 10^{-4} *metric tons* CO_2*/kWh* [25]) which equivalent to eliminating the carbon footprint of the world's electricity consumption over a year.

4. Forest carbon sequestration and harvested wood products carbon storage benefits from mass timber buildings

Trees sequester carbon from the atmosphere during their growth. Harvested trees manufactured into wood products continue to store carbon during the products' lifespans. EWPs used in construction store carbon for extended periods as buildings usually are in service for more than 50-years. With mass timber buildings emerging into the global building sector, even longer lifetimes are expected [26] for buildings that utilize large quantities of mass timber products. Thus, with such buildings, greater service duration and increased carbon storage benefits will potentially be realized.

Carbon stored in buildings with EWPs can be calculated simply using a static method as described in Eq. (1) below:

$$\begin{aligned} \mathrm{CO_2\ stored\,(kg)} &= \mathrm{Volume\ of\ EWP}\left(\mathrm{m^3}\right) \mathrm{x\ Density}\left(\mathrm{kg/m^3}\right) \mathrm{x}\left(1-\mathrm{MC}\right) \\ &\quad \mathrm{x}\left[\mathrm{carbon\ in\ wood}\right] \mathrm{x}\left[\mathrm{Molar\ mass\ of\ CO_2 / Molar\ mass\ of\ C}\right] \end{aligned} \quad (1)$$

- MC – moisture content (%) of EWP
- The carbon in wood is about 50%
- the molar mass of CO_2 is 44; and the molar mass of C is 12.

From Eq. (1), it is clear that carbon stored in EWP depends on the wood species. Common species used to produce mass timber products include fir (*Abies* spp.), Spruce (*Picea* spp.), Douglas fir (*Pseudotsuga menziesii*), larch (*Larix* spp. *Nutt.*), pines (*Pinus* spp.), Western hemlock (*Tsuga heterophylla*), and yellow poplar (*Liriodendron tulipifera Linnaeus*). Their densities (at 12% moisture content) range from 470 kg/m^3 to 627 kg/m^3. Using Eq. (1), it was estimated that carbon storage per m^3 of wood used in mass timber buildings can range from 758 kg CO_2 to 1,012 kg CO_2. Data collected from a few mass timber constructions built in North America, Europe, and Australia indicated that the mass timber volume used in construction ranged from a minimum of 0.08 m^3/m^2 of floor area to a maximum of 0.62 m^3/m^2, with an average of 0.29 m^3/m^2 of floor area. This indicates that an average of 220~293 kg CO_2 can be stored for every m^2 of floor area in a mass timber building.

The Softwood Lumber Board [27] projects that 3.82 billion board feet (bf) (equivalent to 9 million m^3) of softwood lumber will be consumed in mass timber products per year in the U.S. residential and non-residential construction sectors by 2035. Under this assumption, an estimated 6.8 to 9.1 metric tons of CO_2 per year will be stored in those buildings during the buildings' lifespans. In this way, timber buildings fabricated in urban areas may be considered as transferring carbon storage from the forest to the city.

A mass timber building can serve as a carbon reservoir over the building lifespan, which can potentially assist in the mitigation of climate change. Mass timber buildings not only store carbon in the structure, but they can also help sequester more carbon in forests via two mechanisms. First, in a sustainably managed forest, harvesting mature stands and replanting lead to an increased carbon sequestration rate compared to merely maintaining mature stands. Second, increased demand for wood products use in buildings may lead to timber price increases, which may provide economic incentives to invest in intensified forest management activities and/or plantation, which can further lead to increased forest growth and carbon sequestration [16]. When building with wood products, carbon sequestered by trees is transferred into urban buildings and stored for extended periods of time before being released back into the atmosphere upon the building's decommissioning or renovation, through landfill emissions or burning for energy, as depicted in **Figure 4**. Such an extended time delay of carbon emissions has been recognized as an effective way to mitigate climate change.

Figure 4.
Carbon life cycle of the EWPs in construction.

5. Potential environmental impacts from end-of-life design for engineered wood products in buildings

When buildings reach the end of their service life, the materials, after demolition, will either go to landfill or are recycled for reuse and/or substituted for fossil energy. Traditional wood materials used in buildings have a recycle rate of only 27% with the remaining 73% of wood waste from demolition estimated to go to landfills according to the EPA's 2018 C&D management report [28]. Among 27% that are recycled, 22% are reused as compost and mulch, 11% are used in manufacturing wood products, and 67% are burned to generate energy to replace fossil fuel. As mass timber product consumption increases in the building sector in the future, the end-of-life treatment for structural timber may result in a greater recycle rate accompanied by much lower to near zero landfill rate. Several studies have evaluated end-of-life strategies for structural timber or EWPs to understand environmental benefits and economic impacts, using WBLCA and Life cycle cost (LCC) analysis (**Figure 5**).

In WBLCA, the end-of-life (EoL) phase refers to the impacts occurred in Stage C (**Figure 1**). At this stage, activities like deconstruction, waste management (recycling or landfilling), and waste transportation to the landfill are included to examine the total environmental and economic impacts of building materials. The assessments [21, 29–30] revealed a greater recycle/reuse rate for mass timber building products that would reduce not only the global warming potential but also the total life cycle costs of mass timber buildings. Studies [31–33] also have demonstrated the potential benefits at the EoL stage of recycling mass timber EWPs for the same or similar uses in subsequent building construction to extend the carbon storage time. Research [34] was conducted at the USDA Forest Service's Forest Products Laboratory (FPL) on timber recovered from the second Glulam structure built in the US at the FPL. After 75-years' service, minimal degradation of the Glulam beams structural performance was found and the reuse of the product in the same function was attested to be feasible.

The United States and many European countries are implementing stricter regulations for the disposal of wood construction materials in landfills. The reasoning is that while solid wood decomposes very slowly in landfills, it releases biogenic methane, a greenhouse gas with 25 times more global warming potential than carbon dioxide [35]. Thus, EoL strategies that lead to increasing the recycling of demolished wood materials from mass timber construction are expected to contribute positively to the global forest based circular carbon economy.

Carbon accounting at the EoL stage for mass timber EWPs should include CO_2 emissions from deconstruction and transportation of materials to landfills or remanufacturing facilities, and emissions from remanufacturing processes and landfill emissions. Carbon accounting also should include assessing the carbon benefits derived from storage in the products reused or repurposed, storage in landfills, and the substitution of fossil fuels for wood waste in energy recovery.

Previous mass timber building studies using WBLCA and LCC analyses [16, 23], including sensitivity analysis by different recycle rates, have demonstrated that a significant reduction of carbon emissions and total LCC can be achieved with improving EoL building management. With the greater reuse of mass timber construction products, demolition waste is minimized, and salvage values are amplified.

However, such reclamation practices for mass timber buildings also require front-end building materials designed for easy and safe disassembly. Therefore, EWPs and buildings designed with a goal of reuse or recycling are being recognized to have higher environmental and economic benefits. While the economic implications are still unclear, the WBLCA and LCC analyses strongly suggest

Figure 5.
Building life cycle stages for LCA and life cycle cost analysis.

landfills should be avoided, and recycling and reuse should be first principles in waste management for mass timber and EWPs.

6. Conclusions

With their inherent low carbon impact and carbon storage benefits, engineered wood products will play an important role in transforming the built environment from being a major contributor of greenhouse gas emissions to a central solution to the climate crisis. Whole building LCA studies revealed buildings constructed with mass timber, or with a large quantity of engineered wood products, yield significant embodied carbon reductions and are accompanied by large amounts of long term carbon storage, which aids in the mitigation of climate change. Potential avenues for mass timber products end-of-life treatment in construction were examined with LCA and LCC tools to assist policy makers in determining strategies for circularities in material and economy. The increased use of engineered wood and mass timber products in building construction is projected to offer considerable GHG mitigation potential, though the estimated GHG reduction benefits differed widely among studies due to different system boundaries, mass timber products used, and types of building analyzed. Such variability in the results suggests that the carbon benefits of mass timber buildings should not be generalized but should be evaluated on case-by-case basis.

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References

[1] Erol K, Brad D, editors. CLT Handbook. US edition. Library and Archives Canada Cataloguing in Publication; 2013. 572 p. ISBN 978-0-86488-553-1.

[2] United Nations Climate Change. The Paris Agreement. 2016. [Internet]. Available from: https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement [Accessed: 2021-05-01]

[3] Architecture2030.Why the building sector? [Internet]. Available from: https://architecture2030.org/buildings_problem_why/ [Accessed: 2021-05-01]

[4] Rita S, Philip W, Editors. Environmental Life Cycle Assessment – measuring the environmental performance of products. Published by American Center for Life Cycle Assessment; 2014. 315 p. ISBN 978-0-9882145-5-2.

[5] ISO (2006a) 14040: Environmental Management – Life Cycle Assessment – Principles and Framework. International Organization for Standardization, Geneva, Switzerland.

[6] ISO (2006b) 14044: Environmental management – Life cycle assessment – Requirement and guidelines. International Organization for Standardization, Geneva, Switzerland.

[7] ISO 21930:2017. Sustainability in buildings and civil engineering works. Core rules for environmental product declarations of construction products and services. International Organization for Standardization. Geneva, Switzerland.

[8] EN 15978: 2011 Sustainability of construction works – Assessment of environmental performance of buildings – Calculation method. European Committee for Standardization. 60 pp.

[9] Lippke B., E Oneil, R Harroson, K Skog, L. Gustavson, R. Sathre: Life cycle impacts of forest management and wood utilization on carbon mitigation: Knowns and unknowns. Carbon Management. 2011;2:303-333. DOI: 10.4155/cmt.11.24

[10] Skog, KE, DC McKinley, RA Birdsey, SJ Hines, CW. Woodall, ED Reinhardt, JM Vose: Managing Carbon. In: Climate change and United States forests (advances in global change research, 57). 14th ed. Springer; 2014. p. 151-182. DOI: 0.1007/978-94-007-7515-2_7

[11] Brander, M, R tipper, C Hutchison, G Davis. Consequential and attributional approaches to LCA: A guide to policy makers with specific reference to greenhouse gas LCA of biofuels. Technical paper TP090403A. London, UK: Econometrica Press. 14 p.

[12] In: Smulski, Stephen, ed., Engineered wood products-A guide for specifiers, designers and users. ISBN-096556736-0-X. Madison, WI: PFS Research Foundation: pp. 1-1-1-39. Chapter 1. 1997.

[13] Tom W, Robert R, 2016. (Eds.) Proceedings: Mass Timber Research Workshop 2015. General Technical Report FPLGTR-241. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 364 p

[14] Samuel Z, Tom W, Karen M, Michael R, 2019. Research needs assessment for the mass timber industry: Proceedings of the 2nd North American mass timber research needs workshop. General Technical Report FPL-GTR-273. Madison, WI: U.S. Department of Agriculture, Forest

Service, Forest Products Laboratory. 41 p.

[15] WoodWorks. Wood Products Council. [Internet]. Available from: https://www.woodworks.org/why-wood/ [Accessed: 2021-05-01]

[16] Nepal P, KE Skog, DB McKeever, RD Bergman, KL Abt, RC Abt: Carbon mitigation impacts of increased softwood lumber and structural panel use for nonresidential construction in the United States. Forest Products Journal. 2016;66:77-87. DOI: doi:10.13073/FPJ-D-15-00019

[17] Hildebrandt J, N Hagemann, D. Thrän: The contribution of wood-based construction materials for leveraging a low carbon building sector in Europe. Sustainable Cities and Society. 2017;34:405-418. DOI: 10.1016/j.scs.2017.06.013

[18] Smyth C, G. Rampley, TC Lempriere, O Schwab, WA Kurz: Estimating product and energy substitution benefits in national-scale mitigation analyses for Canada. GCB Bioenergy. 2017;9:1071-1084. DOI: 10.1111/gcbb.12389

[19] De Wolf C, Yang F, Cox D, Charlson A, Hattan S, Ochsendorf J, 2016. Material quantities and embodied carbon dioxide in structures. Proceedings of the Institution of Civil Engineers - Engineering Sustainability, 169, 150-161.

[20] Hart J, D'Amico B, Pomponi F, 2021. Whole-life embodied carbon in multistory buildings: Steel, concrete and timber structures. Journal of Industrial Ecology 25(2):403-418. DOI: 10.1111/jiec.13139

[21] Liang S, Gu H, Bergman R, Kelley S, 2020. Comparative life-cycle assessment of a mass timber building and concrete alternative. Wood and Fiber Science. 52(2): 217-229.

[22] Chen Z, Gu H, Bergman R, Liang S, 2020. Comparative life-cycle assessment of a high-rise mass timber building with an equivalent reinforced concrete alternative using the Athena impact estimator for buildings. Sustainability 2020, 12, 4708. DOI:10.3390/su12114708.

[23] Simonen K, Rodriguez X, De Wolf C, 2017. Benchmarking the embodied carbon of buildings. Technology|Architecture + Design, 1, 208-218.

[24] United Nations Environment and International Energy Agency (2017): Towards a zero-emission efficient, and resilient buildings and construction sector. Global Status Report 2017. Pp. 48.

[25] US Environmental Protection Agency. Greenhouse Gases Equivalencies Calculator – Calculations and References. [Internet]. Available from: https://www.epa.gov/energy/greenhouse-gases-equivalencies-calculator-calculations-and-references [Accessed: 2021-05-20]

[26] Michael Green. How Timber Will Define the Skylines of Our Future. [Internet]. 2020. Available from: https://www.woodsolutions.com.au/webinars-podcasts/woodsolutions-weekly-webinars-2020/how-timber-will-define-skylines-our-future-michael-green#:~:text=How%20Timber%20Will%20Define%20the%20Skylines%20of%20Our%20Future%20-%20Michael%20Green,-Submitted%20by%20100content&text=Timber%20is%20an%20important%20ingredient,beautiful%2C%20healthy%20cities%20for%20tomorrow. [Accessed: 2021-05-11]

[27] Southwood Lumber Board. FPInnovations, Ben Romanchych Consulting. Oct. 2020. Mass Timber Outlook. https://softwoodlumberboard.org/wp-content/uploads/2021/03/SLB-Mass-Timber-Outlook-2021-Final-Condensed.pdf [Accessed: 2021-05-01]

[28] U.S. Environmental Protection Agency. Advancing Sustainable Materials Management: 2018 Fact Sheet. [Internet]. 2020. Available from: https://www.epa.gov/sites/production/files/2021-01/documents/2018_ff_fact_sheet_dec_2020_fnl_508.pdf [Accessed: 2021-05-01]

[29] Liang S, Gu H, Bilek T, Bergman R. 2019. Life Cycle Cost Analysis of a Mass Timber Building: Methodology and Hypothetical Case Study. Res. Paper FPL-RP-702. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory: 1-11.

[30] Gu H, Liang S, Bergman R, 2020. Comparison of building construction and life-cycle cost for a high-rise mass timber building with its concrete alternative. Forest Products Journal 70(4):482-492. DOI:10.13073/FPJ-D-20-00052

[31] Chen X, Pierobon F, Ganguly I, 2019. Life cycle assessment (LCA) of cross-laminated timber produced in western Washington: The role of logistics and wood species mix. Sustainability, 11: 1278.

[32] Chen X, 2019. Environmental Assessment of the Production and End-of-Life of Cross-Laminated Timber in Western Washington. Dissertation. University of Washington.

[33] Robertson A, Lam F, Cole R. 2012. A comparative cradle-to-gate life cycle assessment of mid-rise office building construction alternatives: Laminated timber or reinforced concrete. Buildings 2012, 2, 245-270; DOI: 10.3390/buildings2030245

[34] Rammer D, Moura J, Ross R, 2014. Structural Performance of the Second Oldest Glued-Laminated Structure in the United State. Proceedings paper at Structures Congress 2014 © ASCE 2014 https://www.fpl.fs.fed.us/documnts/pdf2014/fpl_2014_rammer001.pdf [Accessed: 2021-05-01]

[35] IPCC Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (Eds.)]. Cambridge University Press. Cambridge, United Kingdom 996 pp.

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