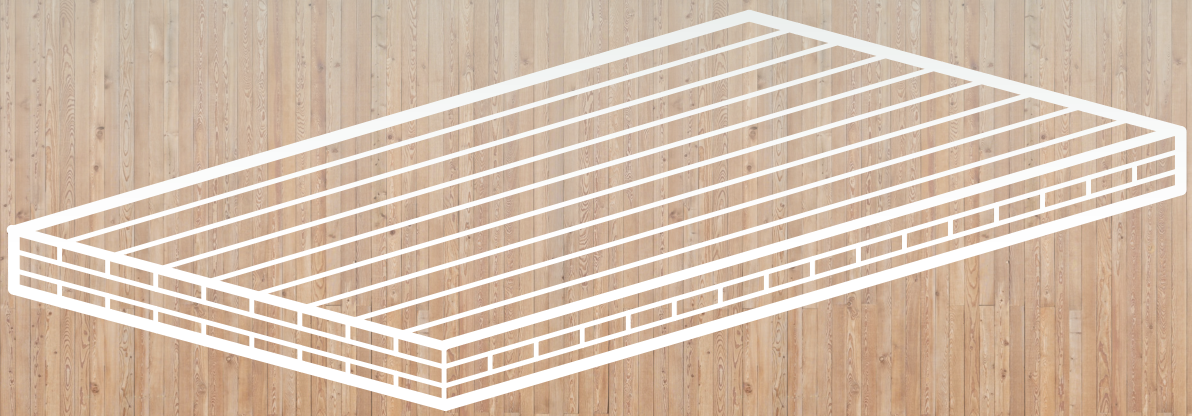

# CROSS-LAMINATED TIMBER
# ANNOTATED BIBLIOGRAPHY

TALLWOOD DESIGN INSTITUTE

Net ZED Case Study Lab

# CLT: Annotated Bibliography



## About

This annotated bibliography provides references for the CLT Info Sheet series. After a comprehensive literature review of data and resources drawn primarily from current studies in Canada and the United States, these sources were selected for their relevance to cross-laminated timber and its embodied carbon (greenhouse gas emissions) and stored carbon. The bibliography came together in a limited amount of time and is not exhaustive; it is meant to be a starting point for the academic and professional audience interested in CLT and its embodied carbon impacts. The foundation of these sources are the life cycle assessment case studies found through searching the terms "CLT" + "LCA" and "CLT" + "Whole Building Life Cycle Assessment" on academic journal databases. Beyond these sources, additional sources were found on industry and trade association websites, manufacturer websites, in print books, and in university publications. For additional information about the info sheets, please refer to the info sheet introduction. This project was conducted under a research grant from the TallWood Design Institute, funded by the USDA Agricultural Research Service under award # USDA-ARS #58-0204-6-002.

The sources are organized by the categories described below. Within the annotated bibliography, to the left of each entry, graphic icons differentiate literature type between journal article, conference proceedings, university publications, reports, periodicals, books, industry & professional practice, and standards

## Categories

**Case Study**
Whole building life cycle assessments or general life cycle assessments of buildings or assemblies containing CLT or wood

**CLT - Code & Standards**
Building codes, standards, and discussion about code requirements for the use of CLT

**CLT - Cost**
Cost information about CLT buildings

**CLT - Industry**
Information and analysis of industry status, market demand, manufacturing process, and product innovations

**CLT - Overview**
General and comprehensive resources for CLT as a material

**CLT & Mass Timber Projects**
Descriptions of current and future CLT building projects

**CLT - Technical**
Research and specifications relating to technical properties and performance of CLT panels

**Forest Management**
Studies and documents about forest management and the calculation of carbon stored in trees and forests

**Life Cycle Assessment (LCA)**
Studies relating to life cycle assessments, carbon accounting, and environmental impacts, often with a focus on wood or other biogenic materials

**LCA - Standards and Product Declarations**
Environmental standards and published documents for life cycle assessments

**Mass Timber**
Information about mass timber products such as DLT and NLT

**Synthesis - Literature Reviews**
Literature reviews and studies analyzing existing available research on a general topic relating to CLT, LCA, or forestry

**User Guides**
Informational guides for WBLCA tools, carbon calculators, and certification programs

## Contents



## Abbreviations

| | |
|---|---|
| **CLT** | Cross-Laminated Timber |
| **$CO_2$eq** | Carbon Dioxide Equivalent |
| **$CH_4$** | Methane |
| **DLT** | Dowel-Laminated Timber |
| **EPD** | Environmental Product Declaration |
| **FSC** | Forest Stewardship Council |
| **IBC** | International Building Code |
| **IPCC** | Intergovernmental Panel on Climate Change |
| **GJ/m$^2$** | Gigajoules per square meter |
| **GWP** | Global Warming Potential |
| **LCA** | Life Cycle Assessment |
| **LVL** | Laminated Veneer Lumber |
| **NLT** | Nail-Laminated Timber |
| **PCR** | Product Category Rules |
| **VOC** | Volatile Organic Compound |
| **WBLCA** | Whole Building Life Cycle Assessment |

## Definitions

**Acidification**
Acidification occurs when an increased concentration of hydrogen ions (H+) alters the acidity of water and soil systems. Acidification and the resulting acid rain can harm ecosystems, plants, animals, buildings, and monuments (Bare, 2012).

**CLT (Cross-Laminated Timber)**
"A prefabricated engineered wood product consisting of at least three layers of solid-sawn lumber or structural composite lumber where the adjacent layers are cross-oriented and bonded with structural adhesive to form a solid wood element" (American Wood Council, 2018, p. 60).

**$CO_2$ eq (Carbon Dioxide Equivalent)**
The cumulative quantity of $CO_2$ and other greenhouse gases (such as methane, or nitrous oxide). The quantities of other greenhouse gases are converted into the equivalent quantity of $CO_2$ that would create the same amount of global warming as the greenhouse gas (Lützkendorf and Balouktsi, 2016).

**DLT (Dowel-Laminated Timber)**
DLT is a panel made of a single layer of standard dimensional lumber pieces friction-fit together on edge with wood dowels (ReThink Wood, 2018).

**GWP (Global Warming Potential)**
Climate change indicator of the sum of greenhouse gas emissions over a period of time, typically expressed in units of **kg $CO_2$ eq**.

**Embodied Carbon**
The sum of greenhouse gases (regardless of type) emitted in one or more life cycle stages of a product, typically expressed by the **impact category** of **global warming potential** and measured in **kg $CO_2$ eq**. For buildings, this usually excludes the embodied carbon associated with operational energy. Embodied carbon is also known as embodied greenhouse gases or carbon footprint.

**Embodied Energy**
The sum of primary energy resources (regardless of their type) consumed or used in one or more life cycle stages of a product (excluding operational energy), typically measured in GJ/kg at a product level or GJ/$m^2$ at a whole building level.

**Environmental Product Declaration (EPD)**
A standardized way of quantifying and documenting a life cycle assessment for a product or system.

**Eutrophication**
Eutrophication refers to the addition of mineral nutrients to soil or water, damaging ecological diversity. In water, nutrients of phosphorus (P) and nitrogen (N) can stimulate the growth of aquatic photosynthetic plant life (algae), which can decrease oxygen in the water and harm aquatic species (Bare, 2012).

**FSC (Forest Stewardship Council)**
An international non-profit, organization that promotes responsible management of the world's forest and administers a forest certification system.

## Definitions

**Impact Category**
An area of environmental concern that may be affected by the use of natural resources in the life cycle of a good or service. An **LCA** often measures multiple impact categories such as **global warming potential**, **acidification** (potential), **eutrophication** (potential), ozone depletion potential, and **smog formation potential**.

**LCA (Life Cycle Assessment)**
Collection and evaluation of the inputs, outputs and the estimated environmental impacts of a product system in its life cycle.

**LCA Software**
Software tools for calculating the environmental impacts of a product or service. Frequently used tools include Gabi, SimaPro, and Open LCA.

**Laminated Veneer Lumber**
An engineered wood product in which thin layers of wood veneers are parallel bonded under heat and pressure, creating a high-strength member primarily used for structural applications.

**Product Category Rules**
A third party document that establishes requirements, and guidelines for developing an **EPD** of a specific product category.

**Smog Formation Potential**
An environmental impact category measuring the contribution of emissions to smog, which is the chemical reaction of sunlight, nitrogen oxides ($NO_x$) and volatile organic compounds (VOCs) in the atmosphere (Bare, 2012).

**System Boundary**
Set of criteria specifying which unit processes are part of a product system. System boundaries include cradle-to-gate (includes only the production stage of a product) and cradle-to-grave (includes product life stages from manufacturing through a product's end-of-life).

**Service Life of Buildings**
The hypothetical life span of a building from construction to demolition.

**Stored/Sequestered Carbon**
The carbon dioxide that is contained within a material as carbon. Wood stores carbon dioxide (as carbon) through photosynthesis, and concrete stores carbon dioxide (as carbon) through the carbonation process.

**Volatile Organic Compound (VOC)**
Volatile organic compounds naturally occur in paint, adhesives and varnish. When they enter the atmosphere, they can aggravate respiratory problems and create smog.

**WBLCA (Whole Building Life Cycle Assessment)**
A methodology to estimate and evaluate the environmental impacts of a building.

**WBLCA Software**
Software tools for calculating the environmental impacts of a building. Examples of software include Athena, Tally, One Click LCA, and LEGEP.

## Literature Types

**Journal Article or Conference Proceedings**
Research from peer-reviewed journals or conference proceedings

**University Publication**
Research from universities, including thesis research

**Reports**
Reports issued by third parties

**Periodicals**
Digital or published magazine articles

**Books or Book Chapters**
Print or e-books

**Industry & Professional Practice**
Resources from professional practice or the wood industry

**Standards**
Codes, standards, product category rules, and environmental product declaration

## Category: Case Study

Whole building life cycle assessments (WBLCA) or general life cycle assessments (LCA) of buildings or assemblies containing CLT or wood

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1. Basaglia, B., Lewis, K., Shrestha, R. & Crews, K. (2014). **A comparative life cycle assessment approach of two innovative long span timber floors with its reinforced concrete equivalent in an Australian context.** *International Conference on Performance-Based and Life-Cycle Structural Engineering,* Brisbane, QLD, Australia, 9-11 December 2015. Brisbane, QLD, Australia: School of Civil Engineering, The University of Queensland. https://doi.org/10.14264/uql.2016.714

**Summary**
Comparison of embodied energy and GWP of design options for a long span floor in a multi-story university building in Sydney, Australia. The compared design options are timber concrete composite, cross-laminated timber (CLT) panel, and typical cast-in-place reinforced concrete. The reinforced concrete floor option has the highest GWP, whereas both timber concrete and CLT floors have a negative GWP due to including stored carbon as a credit. The CLT floor had the lowest global warming potential but the highest embodied energy.
**Scope**: floor system, excluding finishes
**Floor 1**: timber concrete composite (glulam beams attached to a concrete layer)
**Floor 2**: CLT panel
**Floor 3**: reinforced concrete with 20 - 30% fly ash cement replacement mix
**System boundary:** cradle-to-site (with qualitative analysis of construction and end-of-life impacts)
**Service life of floors:** not stated
**LCA data sources**: from 2003 report *Embodied energy and CO2 coefficients for NZ building materials*

2. Borjesson, P., & Gustavsson, L. (2000). **Greenhouse gas balances in building construction: wood versus concrete from life-cycle and forest land-use perspectives.** *Energy Policy*, *28*, 575–588. Retrieved from https://www.sciencedirect.com/science/article/pii/S0301421500000495

**Summary**
A whole building life cycle assessment comparison of primary energy, carbon dioxide and methane emissions of two different structural systems of a four-story residential building in southern Sweden. Additionally, the report compares the carbon storage benefits from different forest management strategies. The embodied energy of the concrete building is generally 60-80% higher than the wood frame building. The net greenhouse gas emissions (GWP) of the timber frame building are usually lower than the concrete building, but the magnitude of difference depends on scenarios: end-of-life scenario for wood, inclusion/exclusion of concrete carbonization, and natural vs. crushed gravel in concrete. The wood frame has a larger GWP than the concrete when the buildings have shorter life spans and when the end-of-life scenario for wood frames is landfilling with no landfill gas collection.

**Scope:** foundations, structural systems with connections
**Light timber building:** concrete slab-on-grade foundations, 120mm thick wood frame outer walls, with 70mm furring wall for wiring and plumbing, light timber joist floor framing
**Concrete building:** not stated
**General building assumptions**: not stated
**System boundary:** cradle-to-grave
**Service life of buildings:** studied at 50 years and 100 years
**LCA data sources**: based on 1995 report from The Norwegian Institute of Building Research

3. Chen, Y. J. (2012). ***Comparison of environmental performance of a five-storey building built with cross-laminated timber and concrete*** (Master's thesis). University of British Columbia. Retrieved from http://baldwin-cf.isri.cmu.edu:8500/colab/crawlers/xcorpus/72.pdf

**Summary**
Comparative study of environmental impacts of embodied energy and operational energy for two five-story office buildings in Burnaby, British Columbia. Continuation of research from Robertson, Lam, & Cole (2012). The production of the CLT building requires 76% more renewable energy but about 18% less of non-renewable energy. In regards to environmental impacts, the CLT building has a 60% lower GWP as well as lower environmental impacts in most categories.
**Mass timber building:** CLT panels and glulam beams, CLT shear walls
**Existing concrete building:** concrete slabs, columns, beams, and shear walls
**System boundary:** cradle-to-gate, operational energy reported separately
**LCA data sources:** not stated

4. Court, A. B., Podesto, L., & Harburg-Petrich, P. (2013). **SEAOC LCA study comparing environmental impacts of structural systems.** In *SEAOC 2013 Convention Proceedings* (pp. 137–153). Retrieved from https://www.seaoc.org/store/ViewProduct.aspx?ID=9630924

**Summary**
A whole building life cycle comparison from the Structural Engineers Association of California (SEAOC) of eight different structural systems (two concrete, two masonry, two steel, and two timber systems) for a prototype 5-story office building in Los Angeles. In general, the relative environmental impacts of the timber structural systems are lower than the steel buildings, and the impacts of the steel buildings are lower than the concrete and masonry. The light timber building has the lowest GWP (4.9 kg $CO_2$ eq./sf), and the heavy timber building has a slightly higher GWP (7.4 kg $CO_2$ eq./sf). The concrete, steel, and masonry structural systems have GWPs that range from 14.5 kg$CO_2$ eq./sf to 21. kg $CO_2$ eq./sf). The only environmental impact where the mass (heavy) timber structural systems has worse environmental impacts is eutrophication. Data source for CLT is not stated.
**Scope**: foundations and 5" concrete slab-on-grade, structural systems with connections
**Light timber building:** wood I-joist floor and roof system, glulam framing, steel lateral bracing
**Mass timber building:** glulam beams and columns with CLT floor and roof systems
**Masonry building:** masonry core walls, steel framing, and steel deck floor with concrete topping
**General building assumptions:** level 1: 14' floor-to-floor height, level 2-5: 12' floor-to-floor height, column bays: 30' O.C. each direction, concrete with 25% flyash substitution, steel recycled content: not stated
**System boundary:** cradle-to-grave (excluding maintenance and replacement)
**Service life of buildings:** not stated
**WBLCA software:** Athena IE v.4.02 (includes customized LCI data for Los Angeles)

5. Dodoo, A., Gustavsson, L., & Sathre, R. (2014). **Lifecycle carbon implications of conventional and low-energy multi-storey timber building systems.** *Energy and Buildings*, 82, 194–210. http://doi.org/10.1016/j.enbuild.2014.06.034

**Summary**
Whole building carbon footprint (embodied carbon) comparison for a four story residential building in Sweden, using a consequential approach. Six different construction systems are compared, including three different timber systems, each with a conventional energy and low-energy alternative. The comparison also includes a sensitivity analysis showing the carbon footprint impact of adjusting data inputs. The CLT low-energy building has the lowest GWP while the conventional beam-and-column building had the highest GWP. Low-energy buildings have approximately 8-9% lower $CO_2$ emissions compared to their conventional counterparts. The study attributes the higher $CO_2$ emissions in the beam-and-column and light frame modular systems to the increased amount of steel and concrete required for these buildings.
**CLT building:** CLT walls, floors, and structural elements (including elevator shaft)
**Timber post-and beam building:** LVL and glulam columns and beams
**Light frame modular building:** individual elements build off-site
**System boundary:** cradle-to-grave, including operational energy (assuming that wood is burned for bioenergy at end of life)
**Service life of buildings:** 50 years (with 100 year service life shown in a sensitivity analysis)
**Software:** ENSYST spreadsheet program for operational energy

6. Grann, B. (2014). ***Wood Innovation and Design Center whole building life cycle assessment.*** Retrieved from FPI Innovations website: https://fpinnovations.ca/Extranet/Pages/AssetDetails.aspx?item=/Extranet/Assets/ResearchReportswp/3126.pdf#.W749RmhKjic

**Summary**
A WBLCA report for the Wood Innovation Design Center, a 4,785 sm (gross floor area) mixed-use building in Prince George, British Columbia compares a mass timber design with a baseline building, seeking to achieve a LEED v4 credit. The mass timber building, compared to the concrete and steel building, achieves at least a 10% reduction in five of the six environmental impact categories tracked by LEED V4, and achieves a reduction in all seven impact categories (Grann, 2014). The mass timber building has a 88% lower GWP than the concrete building, primarily due to the assumption that only 23% of the carbon will decompose in the landfill and return to the atmosphere (Grann, 2014, p. 15). This study excludes the use phases (B1-B7) from the assessment.
**Scope:** Structure & enclosure
**Mass timber building:** glulam beams and columns with CLT floors, CLT core walls
**Concrete building:** reinforced concrete beams and columns
**System boundary:** cradle-to-grave (excluding maintenance, repair, and refurbishment)
**Service life of buildings:** 60 years
**WBLCA Software:** Athena v4.501 (includes data from ecoinvent V3)

7. Griffin, C. T., Reed, B., & Hsu, S. (2010). ***Comparing the embodied energy of structural systems in buildings.*** http://doi.org/10.1201/b15267-133

**Summary**
Comparison of embodied energy of different types of steel and reinforced concrete structural systems, with varying size and material amounts for different span and column sizes. The lowest embodied energy of structural system types and sizes is the one-way concrete slab and beam or one-way joist slab. Steel assemblies have a higher embodied energy than the comparably-sized concrete systems.
**Building assumptions:** 14 foot slab-to-slab height, 42.7% recycled steel content, no fly ash substitution in concrete
**Scope:** structural system, excluding foundations, excluding enclosure and finishes
**System boundary:** cradle-to-grave (excluding maintenance, repair, and refurbishment)
**Service life of buildings:** not stated
**LCA software:** Athena (version not stated)
**LCA data sources:** ICE database

8. Gu, H., Bergman, R. 2018. ***Life cycle assessment and environmental building declaration for the design building at the University of Massachusetts.*** Gen. Tech. Rep. FPL-GTR-255. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 1-73. Retrieved from U.S. Forest Service website: https://www.fs.usda.gov/treesearch/pubs/56321

**Summary**
Report documentation for the LEED certification of the design building at the University of Massachusetts Amherst, a four-story 87,500 sf building in Amherst, Massachusetts. The WBLCA compares the proposed mass timber design with a baseline concrete building. The materials of the mass timber and CLT building have lower environmental impacts in five of six categories excluding eutrophication (no difference). GWP is 13.1% lower for the mass timber building than the steel and concrete building. Operational energy is calculated separately and assumed to be the same for both buildings. Based on an energy mix heavy in natural gas, the operational energy has a greater share of total environmental impacts than the materials (83% of GWP, 85% of acidification, and 87% of fossil fuel depletion).
**CLT reference building:** mixed glulam and structural steel framing with composite CLT-concrete floors, CLT core shear walls, and CLT roof panels.
**Concrete building:** reinforced concrete (with average concrete mixes) and steel
**System boundary:** cradle-to-grave (excluding maintenance, repair, and refurbishment)
**Service life of buildings:** 60 years
**LCA software:** Athena v4.501
**LCA data sources:** U.S. LCI database and ecoinvent V3

9. Guo, H., Liu, Y., Chang, W. S., Shao, Y., & Sun, C. (2017). **Energy saving and carbon reduction in the operation stage of cross laminated timber residential buildings in China.** *Sustainability* (Switzerland), 9(2), 1–17. http://doi.org/10.3390/su9020292

**Summary**
Comparison of operational energy savings and carbon footprints for Chinese residential buildings in locations spread throughout the climate zones of China. The compared buildings are a CLT residential building and a typical reinforced concrete building. The study finds energy savings, varying based on climate zone, when comparing CLT buildings to reinforced concrete buildings. There is up to 29% operational energy savings from CLT buildings, but the greatest energy savings occur in colder climates.
**Scope:** Operational energy for heating and cooling
**System boundary:** Operational phase of building
**Service life of building:** not stated
**Software:** IES (an energy simulation software)

10. Hafner, A., & Schäfer, S. (2018). **Comparative LCA study of different timber and mineral buildings and calculation method for substitution factors on building level.** *Journal of Cleaner Production*, 167, 630–642. http://doi.org/10.1016/j.jclepro.2017.08.203

**Summary**
A whole building life cycle comparison of several single/two family houses and multi-story residential buildings. Within each category, several alternate constructions are considered. Using CLT and light wood frame for single/two family small residential buildings could lower GWP from 35% up to 56% when compared to traditional structures of concrete and brick. Using CLT or light wood frame for multistory buildings could reduce GWP between 9% and 48%. These studies do not include a negative credit for stored carbon in the final result. Neither CLT nor wood frame consistently show more potential than the other to reduce GWP. Multistory wood buildings have increased GWP due to extra fire protection materials required.
**Scope:** foundation, external walls, internal walls, ceiling, roof and balcony if available
**Timber building:** type 1: timber frame with mineral wool insulation, type 2: CLT with mineral wool
**Comparable traditional building 1:** perforated brick and ETICS,
**Comparable traditional building 2:** perforated brick, single leaf
**System boundary:** cradle-to-grave (excluding maintenance and replacement)
**Service life of buildings:** 50 years
**LCA data sources:** oekobau.dat 2015
**WBLCA software:** LEGEP

11. Khavari, A. M., Pei, S., Asce, M., & Tabares-Velasco, P. C. (2016). **Energy consumption analysis of multistory cross-laminated timber residential buildings : a comparative study.** *Journal of Architectural Engineering*, (January 2016). http://doi.org/10.1061/(ASCE)AE.1943-5568.0000206

**Summary**
An operational energy consumption comparison for a 10-story residential building in Sacramento, CA, including a sensitivity analysis for climate, building type, and internal loads. The CLT building shows greater heating energy efficiency with approximately 43% heating energy savings. Overall energy performance is sensitive to variables of climate, building size, internal loading, and HVAC control. The CLT building is less efficient in cooling in the Sacramento climate, and the authors offer several possible reasons: increased airtightness locked in heat, limited natural ventilation, and heat from internal equipment. However, different R values are used for the exterior wall assemblies for the CLT and traditional building, possibly skewing the data. The study also notes that energy used for heating makes up a relatively small portion of overall energy use,
**Mass timber building:** CLT external walls and floors
**Comparable traditional building:** light gauge steel framing
**Assumed internal load:** 6.67 W/m2 from appliances and miscellaneous equipment
**Simulation software:** EnergyPlus 8.2

12. Moncaster, A., & Symons, D. (2013). **An Application of the CEN/TC350 standards to an energy and carbon LCA of timber used in construction, and the effect of end-of-life scenarios**. *ALCAS 8th Life Cycle Conference*, (November 2011).

**Summary**
Comparison of embodied energy and embodied carbon for CLT panels used in the Forte building in New Zealand in relation to end-of-life scenarios. End-of-life scenarios include benefits beyond the system boundary and carbon sequestered in wood panels. Recycling materials at end-of-life is the best scenario for maximizing environmental benefits, followed by incinerating with energy recovery.
**Scope:** CLT Panels
**Service life of building:** not stated
**System boundary:** cradle-to-grave (excluding maintenance and replacement)
**LCA software:** Butterfly

13. Passarelli, R. N. (2018). **The Environmental impact of reused CLT panels : study of a single-storey commercial building in Japan.** *In WCTE 2018 - World Conference on Timber Engineering 2018.*

**Summary**
This study compares the GWP of various CLT reuse scenarios for a small cafe building in Japan and contains lessons learned from the actual reuse of the material. The WBLCA complies with the guidelines of DIN EN 15804:2012+A1:2013 Sustainability of construction works. The four scenarios contain varying amounts of reused CLT: 0%, 50%, 86% (actual building), and 100%. The GWP was lowest for the building with 100% reuse of CLT.
**Scope:** main load-bearing elements and envelope materials
**Service life of building:** 30 years
**System boundary:** cradle-to-grave (excluding maintenance and replacement)

14. Robertson, A. B., Lam, F. C. F., & Cole, R. J. (2012). **A Comparative cradle-to-gate life cycle assessment of mid-rise office building construction alternatives: laminated timber or reinforced concrete**. *Buildings*, 2(4), 245–270. https://doi.org/10.3390/buildings2030245

**Summary**
Whole building life cycle analysis comparison of an existing 14,233 sm office building with a hypothetical mass timber redesign. The mass timber building has a lower environmental impact in 10 of 11 impact categories. Most significantly, the timber building has a 71% lower contribution to GWP when including the carbon storage of wood as a credit (negative) contribution to GWP. The GWP of the timber building is 126 kg $CO_2$ eq./sm compared to 420 kg $CO_2$ eq./sm for the concrete building. The only category where the concrete building has lower impact was a 6% lower fossil fuel depletion. Embodied energy is higher for the mass timber building (8.2 GJ/sm) than the reinforced concrete building (4.6GJ/sm) due to the inclusion of feedstock energy within the wood. The mass timber building has a lower environmental impact in 10 of 11 impact categories. Most significantly, the timber building has a 71% lower contribution to GWP when including the carbon storage of wood as a credit (negative) contribution to GWP.
**Scope:** structure and building enclosure
**Mass timber building:** glulam columns and beams with CLT floors and concrete shear core
**Concrete building:** cast-in-place reinforced concrete
**System boundary:** cradle-to-construction site gate
**Service life of buildings**: 50 years
**LCA software:** none (impacts calculated by authors using multiple data sources)
**Data sources:** BEES® 4.0, and the US LCI Database

15. Skullestad, J. L., Bohne, R. A., & Lohne, J. (2016). **High-rise timber buildings as a climate change mitigation measure - a comparative LCA of structural system alternatives.** *Energy Procedia*, 96(1876), 112–123. http://doi.org/10.1016/j.egypro.2016.09.112

**Summary**
Cradle-to-gate WBLCA of structural systems for 3, 7, 12, and 21 story building versions of a reinforced concrete and equivalent mass timber design. Based on the hotel part of the building Scandic Lerkendal in Trondheim, Norway, the authors apply different calculation approaches, analysis perspective, handling of biogenic CO2 emissions, allocation rules, and accounting for recycling benefits. They find that if 90% of timber production residues and timber material waste is incinerated with heat recovery, replacing natural gas, then the timber structure has a negative global warming potential when considering the avoided impacts of natural gas extraction and combustion. Across calculation approaches and scenarios, the timber structures result in lower global warming potentials than the reinforced concrete equivalents.
**Scope:** foundations and structural systems
**Mass timber building:** glulam framing with CLT floor and roof systems
**Concrete building:** cast-in-place reinforced concrete
**System boundary:** cradle-to-gate A1-A3
**Service life of buildings:** 60 years
**LCA software:** SimaPro v7
**Data sources:** Ecoinvent v.3.2 database, EPDs, information from manufacturers and other studies

16. SOM. (2013). ***Timber tower research project.*** Retrieved from SOM website https://www.som.com/FILE/20378/timber-tower-final-report-and-sketches.pdf

**Summary**
An industry research project to develop a sustainable and cost-competitive structural system for tall buildings. SOM bases their study on an existing 42-story steel and concrete residential building. In addition to structural research, SOM compares embodied carbon for four scenarios: "typical" steel and concrete, "sustainable" steel and concrete, "typical" timber, and "sustainable" timber. SOM proposes a hybrid timber CLT structure as a feasible replacement for the reinforced concrete building. An embodied carbon comparison of a 42-story existing steel and concrete building and the proposed hybrid timber structure shows that the GWP of the hybrid timber structure is 60 to 75% lower than that of the benchmark concrete building structure, even under a scenario allowing for sustainable choices of concrete (less cement) and steel (more recycled content) for the concrete structure. This study includes the carbon storage of wood as a credit (negative) contribution to GWP, and the hypothetical hybrid timber structure includes assumptions about reducing emissions by solely air-drying wood, which may not be feasible for all mass timber products.
**Mass timber building:** 2-story concrete podium, upper floors of glulam columns and beams, CLT floors, CLT shear walls, and steel connections at key locations
**Concrete building:** reinforced concrete floors and columns
**System boundary:** cradle-to-site (including impacts from construction)
**Service life of buildings:** not applicable
**Data sources:** Steel and Concrete - (Hammond and Jones, 2008), Timber - (Puettmann, O'Neil, Milota, and Johnson, 2013).
**WBLCA software:** none stated

17. Stringer, M., & Comber, M. (2015). **Differences in embodied carbon assessments of structural systems.** *In 2015 SEAOC Conference Proceedings* (pp. 131–141).

**Summary**
A whole building life cycle comparison using three different LCA tools (Athena, Tally and SOM Environmental Analysis Tool) for 8 different structural/seismic systems (two concrete, two masonry, two steel, and two timber systems) prototype 5-story office building in Los Angeles. The results show that the wood buildings tend to have lower environmental impact than the steel buildings, which in turn have lower impacts than the concrete or masonry buildings. Results of different LCA tools (Athena, Tally and SOM Environmental Analysis) vary widely, and the variation range for timber systems is up to 40-50%. The impacts for glulam and CLT in Athena and SOM exclude the impacts of adhesives and fabrication.
**Scope:** foundations and 5" concrete slabs-on-grade, structural systems with connections
**Light timber building:** wood I-joist floor and roof system, glulam framing, steel lateral bracing
**Mass timber building:** glulam beams and columns with CLT floor and roof systems
**General building assumptions:** level 1: 14' floor-to-floor height, level 2-5: 12' floor-to-floor height, column bays: 30' O.C. in each direction, concrete with 25% fly ash substitution, steel recycled content: not stated
**System boundary:** cradle-to-grave (excluding maintenance and replacement)
**Service life of buildings:** not stated
**WBLCA software:** Athena IE v.4.02, Tally, and SOM Environmental Analysis Tool

18. Takano, A., Pal, S. K., Kuittinen, M., Alanne, K., Hughes, M., & Winter, S. (2015). **The effect of material selection on life cycle energy balance: A case study on a hypothetical building model in Finland.** *Building and Environment*, 89, 192–202. https://doi.org/10.1016/j.buildenv.2015.03.001

**Summary**
Comparative study of life cycle primary energy balance (renewable and non-renewable) between nine different structural frame systems, including a CLT option. Part two of the study compares primary energy balance of sheathing, flooring, roofing, and exterior cladding materials. The CLT structure requires the most energy for its production, but also has the greatest potential benefits beyond the system boundary in end-of-life.

19. Teshnizi, Z., Pilon, A., Storey, S., Lopez, D., & Froese, T. M. (2018). **Lessons learned from life cycle assessment and life cycle costing of two residential towers at the University of British Columbia.** *Proceedings of the 25th CIRP Life Cycle Engineering (LCE) Conference* (pp. 172–177). University of British Columbia. https://doi.org/10.1016/j.procir.2017.11.121

**Summary**
A whole building life cycle assessment and cost comparison between two eighteen-story buildings at the University of British Columbia, in Vancouver, Canada: a mass timber design (the Tallwood House) and a comparable existing building (the Cedar House). Excluding operational energy impacts, Tallwood House has roughly 9% lower negative impacts in five out of six environmental impact categories. Solely considering the impacts of the structure, the mass timber CLT building considerably has much lower impacts than the concrete building, even when including the multiple layers of Type X gyp board. This includes GWP, where the timber building is 36% lower. In the life cycle cost comparison, the timber building has an overall 7% higher cost per square meter, with an 11% higher construction cost. The authors of the study note that this is partially due to an innovation premium and is expected to go down as contractors become more familiar with the material.
**Mass timber building:** cast-in-place concrete foundation, ground floor, second-floor slab, and stair/elevator cores. CLT upper floors supported on glue-laminated timber (GLT) and parallel strand lumber (PSL) columns with steel connections, and a steel roof deck.
**Comparable concrete building:** Reinforced concrete foundation and basement, reinforced concrete stair/elevator cores. Two-way reinforced concrete suspended slabs with concrete columns and a concrete roof structure.
**System boundary:** cradle-to-grave (including maintenance, repair, refurbishment, and operational energy)
**Service life of buildings:** 100 years
**LCA software:** Athena

## Category: Codes & Standards
Building codes, standards, and discussion about code requirements for the use of CLT.

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1. American Wood Council. (2015). ***2015 code conforming wood design.*** Leesburg, VA. Retrieved from AWC website: https://www.awc.org/pdf/building-codes/ccwd/CCWD_Complete_2015.pdf

   **Summary**
   Guidance for wood usage and design for conformance with the 2015 International Building Code. The instructional guide interprets each building code section that applies to wood construction materials such as CLT.

2. American Wood Council (AWC). (2017a). ***National design specification (NDS) for wood construction. ANSI/AWC NDS-2018.*** Leesburg, VA: AWC

   **Summary**
   Provides reference design values and specifications for wood products, including CLT. Specifies adjustment factors to be multiplied by manufacturer's specific reference design values.

3. American Wood Council (AWC). (2017b). ***NDS Supplement national design specification design values for wood construction.*** Retrieved from https://www.awc.org/pdf/codes-standards/publications/nds/AWC-NDS2018-Supplement-ViewOnly-171027.pdf

   **Summary**
   Compendium of reference design values and grading for structural sawn lumber, structural glued laminated timber, and round timber piles and poles. Lumber design values are based on the lumber grading information found in grading rules published by seven North American grading agencies. Visual grades of common CLT lumbers, such as spruce-pine-fir, douglas fir, and larch are noted in these design value tables.

4. APA - The Engineered Wood Association. ***(2018). ANSI/APA PRG 320-2018: Standard for performance-rated cross-laminated timber.*** Tacoma, WA.

**Summary**
First developed in 2010, this standard provides definitions, requirements, and test methods for structural cross-laminated timber. Standards encompass panel dimensions, dimensional tolerances, lumber properties, adhesive requirements, performance criteria, and manufacturing plant requirements. Specifies seven product performance classes for CLT.
**Panel thickness:** Overall thickness of the panel may not exceed 20 inches.
**Layer thickness:** Minimum thickness of 5/8" and maximum thickness of 2"
**Parallel layers:** Wood must be a minimum visual grade #2 or 1200f-1.2E MSR
**Perpendicular layers**: Wood must be a minimum visual grade #3
**Lamination sizes:** Lamination width shall not be less than 1.75 times the lamination thickness at parallel layers.
**Allowed wood species:** any softwood lumber species recognized by American Lumber Standards Committee or Canadian Lumber Standards Accreditation Board, with a minimum published specific gravity of 0.35.
**Moisture content at manufacturing:** shall be 12 ± 3%.

5. Francis, S., & Coats, P. (2018). **Outcomes of ICC tall wood ad hoc committee : proposals and discussion.** Retrieved from https://www.awc.org/pdf/education/des/AWC-DES605-TWBProposals-180403.pdf

**Summary**
An AIA continuing education presentation of the proposed 2021 International Building Code changes recommended by the Tall Wood Building Ad Hoc Committee, which will allow for expanded approved usage of CLT and mass timber in tall buildings. The 2021 International Building Code will contain fifteen key code changes, including a codified definition of mass timber, and three new subtypes of construction within type IV construction.

6. International Code Council. (2015). **2015 International Building Code: chapter 6.** Retrieved from ICC website https://codes.iccsafe.org/content/IBC2015/ chapter-6-types-of-construction?site_type=public

**Summary**
International Building Code (2015) chapter with building type requirements for type IV heavy timber. CLT is approved for usage in floors and walls in type IV heavy timber buildings. For use in floors, cross-laminated timber shall be not less than 4 inches (102 mm) in thickness, shall be continuous from support to support and mechanically fastened to one another. CLT can be used in exterior wall assemblies, provided the assemblies require a 2-hour rating or less if the CLT is protected by at least one of the following: fire-retardant-treated wood sheathing not less than 15/32 inch (12 mm) thick; gypsum board not less than 1/2 inch (12.7 mm) thick, or a noncombustible material.

7. Kretschmann D. E.; Evans J. W; Brown, L. (2010). ***Chapter 7 - Stress grades and design properties for lumber, round timber and ties.*** In Wood Handbook - Wood as an engineering material (pp. 1–16).

**Summary**
Book chapter discussing stress grades and design properties for lumber, round timber, and ties. Describes visual and machine graded lumber and the organizations that regulate lumber grading.

8. Locke, T. (2018). **A big win for tall wood.** Retrieved December 26, 2018, from https://www.oregonforests.org/node/620

**Summary**
News article announcing the voting results approving fourteen tall wood building changes for the 2021 International Building Code, pending certification by the International Code Council Committees. The changes include three new mass timber construction types.

9. Mayo, J., Blomgren, H.-E., Powers, J., Gerard, R., Jones, S., Richardson, D., & Hackett, J. (2018). ***Mass timber/CLT & Washington building codes: a technical primer.*** Retrieved from Forterra website: https://forterra.org/wp-content/uploads/2018/03/WA-BCTP-Jan.-2018-002.pdf

**Summary**
An overview of how mass timber materials, primarily CLT, fit into building code, with a focus on Washington building codes. CLT is already code-approved for structural use in gravity systems (e.g. floors, beams, columns, load-bearing walls) as a heavy timber material for buildings up to 85 ft tall. However, using CLT for lateral, seismic force resisting systems, as defined by the IBC, currently requires using the alternative means and methods for approval. The primer also provides an overview of the new building types (type IV-A, type IV-B, and type IV-C) that will be incorporated into the 2021 International Building Code.

10. Post, N. M. (2015). **Going against the grain**. *ENR*, 36–41. Retrieved from https://www.ecobuilding.org/code-innovations/case-study-related-files/enr-going-against-the-grain-clt-codes

**Summary**
Discusses code compliance of mass timber construction, advantages and disadvantages of mass timber construction, and future developments. Contains interview content from design and engineering professionals currently working with mass timber. CLT material has a two-way span but is slightly weaker than some other laminated products, and loses floor slab cost efficiency at spans over 20 ft. Future wood innovations could be 3D printed wood beams or genetic engineering to produce stronger trees.

11. WoodWorks Wood Products Council. (n.d.). **Prescriptive or engineered design.** Retrieved November 11, 2018, from http://www.woodworks.org/design-and-tools/design-topics/prescriptive-or-engineered-design/

**Summary**
Web page describing differences between prescriptive and engineered paths to code compliance in new buildings.

**Category: CLT - Cost**
Cost information about CLT buildings

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1. Atlantic WoodWorks. (2016). ***Mid rise wood: opportunities for Atlantic Canadian urban centres.*** Retrieved from http://wood-works.ca/wp-content/uploads/Wood-4-Mid-Rise-12-page-case-study-sm.pdf

**Summary**
This report studies opportunities for six story wood buildings in Atlantic Canadian centers: Fredericton, Charlottetown, Halifax, and St. John's. The report consists of a market study, a cost analysis, a review of building code changes, and a comparison of construction types. They compare the cost of four different construction systems for a six story mixed use (five stories residential over one story retail) building: five levels of wood above one concrete story, six levels steel, six levels concrete, and six levels of wood construction. The wood buildings have CLT for some of the structural elements, but the exact application is not noted. The report finds that the wood buildings are the least expensive to build, despite having larger insurance costs than the steel or concrete.

2. Cary Kopczynski & Company. (2018). ***Cross laminated timber feasibility study.*** Retrieved from http://buildingstudies.org/pdf/related_studies/Cross_Laminated_Timber_Feasibility_Study_Feb-2018.pdf

**Summary**
Cost comparison and CLT feasibility study for a 10-story residential building structure in the Pacific Northwest. The study compares a CLT building to an equivalent reinforced concrete building. The cost of the CLT structure (estimated $48 to $56 per gross square foot) is approximately 16 to 29% greater than the cast-in-place reinforced concrete structure (estimated $42 to $46 per gross square foot). However, the included structural diagrams seem to indicate a lack of equivalence between the two compared structures. The concrete system does not include interior walls that are necessary to be identical to the partition layout with the CLT structural system. This lack of equivalence could contribute to CLT's cost premium. A lack of material quantities prevents verification of these costs.
**Concrete building:** 16"x24" reinforced concrete columns with 9" thick reinforced concrete slabs
**CLT building:** bearing wall system made up of 5-layer CLT walls with 5 and 7-layer floors
**General building assumptions**: in all compared buildings, all interior non-load-bearing partitions are metal stud
**Scope:** material and construction cost

3. Mahlum, Walsh Construction Co., & Coughlin Porter Lundeen. (May 14, 2014). ***A Study of alternative construction methods in the Pacific Northwest.*** Retrieved from http://www.mahlum.com/pdf/PNWCLTFeasibilityReport.pdf

**Summary**
A cost comparison of 8-story material systems for a residential building atop a 2-story concrete podium in Seattle, Washington. The study finds a 4% cost savings for the CLT building compared to the concrete building. The metal stud option offers a 2% cost savings compared to the concrete building. Although they do not specifically calculate construction time, the authors believe significant construction time savings could result from prefabricated CLT panel use.
**Concrete building:** 7"post-tensioned concrete floor, 5" post-tensioned concrete roof, and concrete columns
**Metal stud building:** metal stud walls, concrete shear walls, metal decking floor and roofs with a 3" concrete toping
**CLT building:** 5-layer CLT load-bearing walls and 3-layer CLT non-load-bearing walls
**General building assumptions:** in all compared buildings, all interior non-load-bearing partitions are metal stud
**Scope:** material and construction cost, including additional layers of gypsum board for CLT fire protection

4. Hyams, A., Watts, S., & Harvatt, C. (2017). ***Residential timber cost model.*** Retrieved from https://www.trada.co.uk/publications/info-from-other-organisations/residential-timber-cost-model/

**Summary**
Cost comparison between a CLT and concrete structural design for a seven-story residential building in London. The analysis includes costs for substructure, above-ground structure and finishes, and contractor costs. There is less than a 1% total building cost difference between the CLT and concrete buildings.
**Concrete building:** reinforced concrete frame with concrete core walls
**CLT building:** non-visual grade CLT frame, upper floors, roof, core, stairs, and external walls with concrete foundations
**Scope:** material and construction cost, including additional layers of gypsum board for CLT at interior walls and ceilings due to acoustic, fire, and visual requirements

## Category: CLT - Industry

Information and analysis of industry status, market demand, manufacturing process, and product innovations.

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1. Chouinard, P. (October 5, 2017). **The Evolution of CLT manufacturing in North America.** Retrieved November 15, 2018, from http://www.wooddesignandbuilding.com/the-evolution-of-clt-manufacturing-in-north-america/

**Summary**
A discussion of future CLT manufacturing expansion and the capabilities of the vacuum press method of CLT panel creation, in place of the traditional hydraulic press method for fabricating CLT panels. CLT is expensive to transport long distances, and new manufacturers will be necessary to make CLT buildings economically feasible throughout North America. Manufacturing will be likely to expand with vacuum press facilities, which are less costly than the hydraulic presses that are commonly used (approximately CDN $375,000 compared to CDN $10 to $25 million for hydraulic presses).

2. Grasser, K. K. (2015). **Development of cross laminated timber in the United States of America.** University of Tennessee, Knoxville. Retrieved from https://static1.squarespace.com/static/559921a3e4b02c1d7480f8f4/t/59a7c7b3f14aa112f0135d6f/1504167869987/GrasserKarlKonstantin_394.pdf

**Summary**
Examines the existing CLT industry and economic climate in Europe and the United States. The thesis also diagrams and documents the processes and layout of a CLT manufacturing facility, in order to determine the feasibility of yellow poplar CLT. Yellow poplar could successfully meet functional requirements of wood used in a CLT panel, but the higher cost of yellow poplar may prove restrictive.

3. Imarc Group. (2019a). ***Press release: cross-laminated timber market : Global industry trends, share, size, growth, opportunity and forecast 2019-2024.*** Retrieved May 23, 2019, from https://www.imarcgroup.com/cross-laminated-timber-manufacturing-plant

**Summary**
Market research firm's summary of key insights into the value of the global CLT industry. The primary drivers of global CLT market growth include short construction times and flexibility of application. The global cross-laminated timber market was valued at US$ 664 million in 2018. The market value is expected to grow by 13.4% (compound annual growth rate) from 2019 to 2024 to reach a value of US$ 1,457 million by 2024.

4. Imarc Group. (2019b). ***Press release: North America cross-laminated timber market : Industry trends, share, size, growth, opportunity and forecast 2019-2024.*** Retrieved May 23, 2019, from https://www.imarcgroup.com/north-america-cross-laminated-timber-market

**Summary**
Market research firm's summary of key insights into the value of the North American CLT industry. Growing environmental concerns, prefabrication construction speed, and desirable aesthetic drive North American CLT market growth. The North American cross-laminated timber market was valued at US $59.73 million in 2018. The market value is expected to grow from 2019 to 2024 to reach a value of US $171 million by 2024.

5. Muszyński, L., Hansen, E., Fernando, S., Schwarzmann, G., & Rainer, J. (2017). **Insights into the global cross-laminated timber industry.** *Bioproducts Business*, 2(8), 77–92.

**Summary**
Qualitative findings from a 2016 questionnaire that an Oregon State University research team sent out to 21 CLT manufacturers. Although CLT manufacturing is still concentrated in central Europe, it is slowly growing in the United States. Most CLT is custom-produced for small to medium size residential, public, and industrial structures, not tall buildings.

6. Oregon Best. ***Advanced wood product manufacturing study for cross-laminated timber acceleration in Oregon & SW Washington, 2017*** (2017). Retrieved from http://oregonbest.org/fileadmin/media/Mass_Timber/Accelerating_CLT_Manufacturing_in_Oregon___SW_Washington__2017__Oregon_BEST_.pdf

**Summary**
Regional stakeholders analyze the development potential for CLT production in Oregon and Southwest Washington, with the goal of accelerating CLT manufacturing in these regions. The report details the industry background, natural resource capacity, capable producers, economic impact, market barriers, and future projects. In Oregon and Southwest Washington, increased CLT production offers economic benefits and existing forest resources could accommodate additional wood demand. Barriers to CLT market growth include education and code compliance concerns.

7. Plackner, H. (2014). **"Then let's do it ourselves " three companies are having their own glueless CLT lines installed.** Retrieved December 2, 2018, from https://www.timber-online.net/holzbau/2014/06/_then_let_s_do_itourselves.html

**Summary**
News article about three German companies who are installing glueless CLT manufacturing lines. In Germany, glueless CLT is commonly known as MHM (Massiv-Holz-Mauer in German, "solid wood wall" in English). Manufacturers identify key advantages of glueless CLT as being cheaper and reducing construction time.

8. Portland Design. (2018). **REclaiming wood: deconstruction initiatives, upcycling into CLT, and more.** Event web page. Retrieved from https://portlanddesign.org/event/reclaiming-wood-deconstruction-initiatives-upcycling-into-clt/

**Summary**
Description of mass timber event with a focus on reusing wood in the construction industry.

9. Smith, R. E. (2011). **Interlocking cross-laminated timber : alternative use of waste wood in design and construction.** *In BTES Conference 2011 – Convergence and Confluence* (p. 22). Retrieved from http://citeseerx.ist.psu.edu/viewdoc/ download?doi=10.1.1.475.2367& rep=rep1&type=pdf

**Summary**
Highlights the research and development of interlocking cross-laminated timber, which does not use adhesives or metal fasteners. Interlocking CLT can utilize beetle-kill pine trees that otherwise would simply decay in the forest. Interlocking CLT could be a cost-competitive and environmentally superior choice for 3-9 story buildings.

10. Texas A&M Forest Service. (2018). **Cross laminated timber ( CLT ) talking points**, (October). Retrieved January 01, 2019, from https://tfsweb.tamu.edu/uploadedFiles/TFSMain/Data_and_Analysis/Forest_Economics_and_Resource_Analysis/Contact_Us(3)/CLT talking points.pdf

**Summary**
Informal introduction to cross-laminated timber and information about current and planned projects and manufacturers. European companies currently manufacture approximately 80% of the world's CLT, but several new manufacturers are planning additional facilities in North America.

## Category: CLT - Overview

General and comprehensive resources for CLT as a material

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1. Crespell, P., & Gagnon, S. (2010). ***Cross laminated timber: a primer.*** FPInnovations. Retrieved from https://fpinnovations.ca/media/factsheets/Documents/cross-laminated-timber-the-boook.pdf

**Summary**
Overview of CLT's development and usage. The presentation describes the basic characteristics of CLT and includes imagery of some typical CLT construction assemblies.

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2. Exnova BMTRADA. (2017). ***Cross-laminated timber: design and performance.*** Exova (UK) LTD.

**Summary**
Overview of CLT as a building material, with a focus on usage in the United Kingdom. The book contains many construction details and project examples. Fourteen case studies describe the CLT systems in varied European projects.

3. Karacabeyli, E., & Brad, D. (2013). ***CLT Handbook: US Edition***. Book. Pointe-Claire, Québec: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory, Binational Softwood Lumber Council (BSLC). https://doi.org/10.1017/CBO9781107415324.004

**Summary**
572-page, comprehensive overview of CLT. In addition to a history and description of CLT, it provides design and technical guidance (including structural, fire, environmental, and construction) in twelve chapters.

4. Mohammad, M., Gagnon, S., Douglas, B., & Podesto, L. (2012). **Introduction to cross laminated timber.** *Wood Design Focus*, 22(2), 3–12. Retrieved from http://www.forestprod.org/buy_publications/resources/untitled/summer2012/Volume 22, Issue 2 Mohammad.pdf

**Summary**
An introduction to CLT's usage, benefits, challenges, and strategies. This article focuses on CLT in the context of Canada and the United States.

5. Sutton, A., Black, D., & Walker, P. (2011). ***Cross-laminated timber: an introduction to low-impact building materials. Information Paper - IP17/11.*** Retrieved from the BRE website: https://www.bre.co.uk/filelibrary/pdf/projects/low_impact_materials/IP17_11.pdf

   **Summary**
   United Kingdom-focused overview of CLT, its benefits and challenges, and general design strategies. The authors present the structural and thermal properties of CLT as a key advantage, as well as the potential for faster construction. Key challenges are keeping CLT dry on construction sites, and having a fully-determined design before panel production.

6. Waugh Thistleton Architects. (2018). ***100 projects: UK CLT.*** Retrieved from https://www.thinkwood.com/clt100book

   **Summary**
   A general overview of CLT and case studies of 100 CLT buildings in the United Kingdom. Partially because UK building regulations are performance-based (rather than prescriptive), CLT buildings are widespread in the UK. The e-book contains descriptions of various CLT systems, design recommendations, and in-depth case studies with compelling visual graphics.

## Category: CLT & Mass Timber Projects

Descriptions of current and future CLT and other mass timber building projects

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1. Alter, L. (2012). **Fort McMurray Airport is the largest cross laminated timber building in North America.** *Treehugger*. Retrieved April 26, 2019, from https://www.treehugger.com/green-architecture/fort-mcmurray-airport-largest-cross-laminated-timber-building-north-america.html

**Summary**

An article about the use of CLT in the Fort McMurray Airport. The 170,000 sf airport uses CLT panels that contain approximately 50% Japan-grade beetle-kill pine, which is beetle-kill wood without a blue stain. The airport's design also features sustainable strategies like daylighting, passive ventilation, and heat recovery.

2. Hill, D. (2015). **Less than zero**. *Architect,* (December). Retrieved from https://www.architectmagazine.com/post-occupancy-study-rocky-mountaininstitute-goes-net-zero

**Summary**

Description of sustainable features that contribute to the Rocky Mountain Institute for Innovation's net zero design. The building is passively heated and cooled, and the structure features CLT floors comprised of wood from beetle-kill pine trees.

3. Hummel, B. (2018, October 12). **Timber in Georgia's first living building.** Retrieved November 12, 2018, from http://gfagrow.org/timber-in-georgias-first- living-building/

**Summary**

Web article about the Kendeda Building for Innovative Sustainable Design on the Georgia Institute of Technology campus. The building aims to achieve Living Building Challenge certification, and utilizes NLT panels made from reused lumber.

4. Lubell, S. (2017, November 17). **Studio Ma designs net-zero timber building for Arizona State.** Retrieved December 13, 2018, from https://archpaper. com/2017/11/studio-ma-net-zero-timber-arizona-state/

**Summary**

Arizona State University's Interdisciplinary Technology Building, currently planned for 2020 completion, will utilize CLT floors and is designed to be zero net energy, zero waste and zero net greenhouse gas emissions.

## Category: CLT - Technical

Research and studies relating to technical properties and performance of CLT panels.

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1. Aicher, S., Hirsch, M., & Christian, Z. (2016). **Hybrid cross-laminated timber plates with beech wood cross-layers.** *Construction and Building Materials*, 124, 1007–1018. http://doi.org/10.1016/j.conbuildmat.2016.08.051

**Summary**
Research study from the Materials Testing Institute (MPA) at the University of Stuttgart, investigating the shear properties of using a beech hardwood center layer within a 3-layer configuration of CLT. Adding a layer of hardwood improves rolling shear properties in the CLT. Large stands of beech in Central Europe are promising sources for this CLT material.

2. Buck, D., Wang, X. A., Hagman, O., & Gustafsson, A. (2016). **Bending properties of cross laminated yimber (CLT) with a 45˚ alternating layer configuration.** *BioResources*, 11(2), 4633–4644. http://doi.org/10.15376/biores.11.2.4633-4644

**Summary**
Research from Luleå University of Technology testing bending and load bearing for typical CLT panels compared to CLT panels with 45˚ diagonal interior layers. Bending strength for 45˚ CLT is 35% greater than the CLT 90˚ layers.

3. Egoin. (n.d.). **Materials and Products: Ego_CLT and Ego_CLT Mix.** Retrieved October 25, 2018, from http://www.panelesclt.com/documentos/catalogo-clt-egoin_eng.pdf

**Summary**
Product information guide for Egoin's CLT and their Ego_CLT Mix product (CLT cassette panels).

4. Element5. (n.d.). **ELEMENT5: Products.** Retrieved from https://elementfive.co/products/

**Summary**
Information on Element 5's various CLT panels, including cassette panels.

5. Ganey, R. (2015). ***Seismic design and testing of rocking cross laminated timber walls.*** University of Washington. Retrieved from https://digital.lib.washington.edu/researchworks/handle/1773/33664%0A

**Summary**
A feasibility evaluation of the ability of a rocking CLT wall system in 8 to 14 story buildings to respond to seismic hazards in Seattle. Simulations are performed in OpenSees. Results of testing the system indicate that a rocking CLT wall system provides a ductile response and good energy dissipation.

6. Pei, S., van de Lindt, J.W., Popovski, M., Berman, J. W., Dolan, J. D., Ricles, J., Sause, R., Blomgren, H., & Rammer, D. R. (2014.). **Cross-laminated timber for seismic regions : progress and challenges for research and implementation.** *Journal of Structural Engineering,* (July 2014). http://doi.org/10.1061/(ASCE)ST.1943-541X.0001192

**Summary**
Comprehensive discussion of CLT's potential structural use in seismic regions. Although CLT has well-established properties for gravity force-resisting, CLT systems for lateral and/or seismic force resistance are still being researched. The document includes information on published tests of CLT seismic performance. During seismic testing, CLT walls experience the most damage at connections (which deform and thus provide ductility to the wall. For CLT buildings in high seismic regions, a performance-based seismic design (or no damage design) philosophy should be adopted. Using traditional force-based seismic design approaches for CLT results in connection deformation, high accelerations, and correspondingly large base shear 1and uplift demands.

7. Quenneville, P., & Morris, H. (2007). **Japan Kobe earthquake shake table simulation.** *NZ Timber Journal*, 15(4), 3–8.

**Summary**
Results of a simulation shake test on a seven story CLT building mock up in Japan. The building underwent a simulation of the intensity of the Kobe earthquake, which resulted in no residual deformation of the structure and minor softening. The maximum inter-story drift was 40mm, and the maximum lateral deformation was under 300mm.

8. Smith, R. E., & Kretschmann, D. (2013). **Research in progress: Solid timber from blue stain beetle killed ponderosa pine: phase 1.** Coalition for Advanced Wood Structures.

**Summary**
Research update for a project to optimize interlocking cross-laminated timber panels using beetle kill pine. The research primarily investigates dimensional and fabrication optimization.

9. Stora Enso. (n.d.). ***Thermal inertia of Stora Enso projects CLT in comparison to other building materials such as masonry or concrete.*** Retrieved December 19, 2018, from http://www.clt.info/en/product/technical-specifications/thermal-inertia/

**Summary**
Thermal analysis by Stora Enso comparing the following walls in the environment of Vienna, Austria: 10 cm CLT wall, 20 cm CLT wall, light wood frame wall, masonry wall, and concrete wall. A discomfort metric (the amount of hours in which the internal temperature was over 27 degrees Celsius) was used to compare wall assemblies. Although the concrete wall performs better than the CLT walls, the CLT walls perform comparably to the masonry wall.

10. Structurlam. (2016). ***CrossLam CLT technical design guide v4.0***. Retrieved from Structurlam website: http://structurlam.com/wp-content/uploads/2016/08/Structurlam-Design-Guide-August-2016-low-res-Metric.pdf

**Summary**
32-page manufacturer design guide for Structurlam's CrossLam CLT.

11. Structurlam. (2017, June 12). ***Concrete vs . CLT***. Retrieved December 14, 2018, from https://www.structurlam.com/whats-new/uncategorized/concrete-vscross-laminated-timber/

**Summary**
Manufacturer web article promoting the benefits of CLT over concrete construction. Promised CLT advantages include: resilient seismic performance, reduced construction time, improved sustainability, and decreased cost.

12. USDA Forest Products Laboratory. (n.d.). **Research in progress: engineering performance characteristics of hardwood cross-laminated timber.** Retrieved February 19, 2019 from https://www.fpl.fs.fed.us/documnts/rips/fplrip-4714-034-MTU-Xie-Wang.pdf

**Summary**
Announcement of research in progress of a feasibility study for hardwood CLT in Michigan.

## Category: Forest Management

Studies and documents about forest management and the calculation of carbon stored in trees and forests.

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1. Diaz, D. D., Loreno, S., Ettl, G. J., & Davies, B. (2018). **Tradeoffs in timber, carbon, and cash flow under alternative management systems for Douglas-Fir in the Pacific Northwest.** *Forests,* 9(8), 1–25. https://doi.org/10.3390/f9080447

**Summary**

Comparison of the effects of four forest management options on three categories: average carbon storage in the forest and wood products, cumulative timber output, and discounted cash flow. The study scope is 64 randomly chosen Douglas fir forests across western Oregon and Washington. The study finds that FSC practices (of increased riparian buffers, increased green tree retention, and longer rotation periods) increase carbon storage potential above business-as-usual, state-required forest management practices. FSC practices are more costly. Washington's forest management practices are closer to FSC practices than Oregon's.

2. Coast Range Forest Watch. (2015). ***Research and resources on the negative effects of pesticide and aerial spray.*** Retrieved from https://coastrangeforestwatch.org/research-and-resources-on-the-negative-effects-of-pesticide-and-aerial-spray/

**Summary**

Summary of research on the negative impacts of pesticides and aerial spray. Long-term exposure to common logging industry pesticides like glyphosate, 2,4-D and atrazine can injure the liver and kidneys. Pesticides pervade water sources and are currently not well regulated with regard to inert ingredients.

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3. Cox, C., & Surgan, M. (2006). **Commentary unidentified inert ingredients in pesticides : Implications for human and environmental health.** *Environmental Health*, 114(12), 1803–1806. http://doi.org/10.1289/ehp.9374

**Summary**

Pesticides have both active and inert ingredients, with the active ingredients currently requiring more testing and labeling in the United States. Inert ingredients are known to have toxic effects, such as developmental neurotoxicity, genotoxicity, and disruption of hormone function. They can also increase exposure in humans, animals, and environments. Thus pesticide regulation should include requirements for inert ingredients and full formulation considerations.

4. Fain, S. J., Kittler, B., & Chowyuk, A. (2018). **Managing moist forests of the Pacific Northwest United States for climate positive outcomes.** *Forests*, 618(9), 1–20. http://doi.org/10.3390/f9100618

**Summary**

Refer to Synthesis - Literature Review

5. Gorte, R. (2009). ***Carbon sequestration in forests and soils.*** CSR Report for Congress. Retrieved from https://www.annualreviews.org/doi/10.1146/annurev-resource-083110-115941

**Summary**
Overview of research on carbon sequestration in forests and soils, as well as suggested policies. This congressional report covers biological processes of carbon sequestration, methods of carbon accounting, and the current status of forests. Ultimately, it suggests three main government policies to increase carbon stored in forests in the United States: implement more carbon-sequestering forestry practices on federal lands, provide technical and financial assistance for forest management practices to private landowners, and tax incentives to encourage carbon-sequestering forestry practices by private landowners.

6. Harmon, M. E., Moreno, A., & Domingo, J. B. (2009). **Effects of partial harvest on the carbon stores in douglas-fir/western hemlock forests: a simulation study.** *Ecosystems,* 12(5), 777–791. http://doi.org/10.1007/s10021-009-9256-2

**Summary**
This study uses the STANDCARB 2.0 model to compare carbon storage effects from various rotation intervals and partial harvests in the context of Pacific Northwest forests. Increasing the interval between harvests increases the amount of carbon stored in the forest. Although decreasing harvest intervals can potentially increase the amount of carbon stored in forest products, carbon storage in the forest does not immediately offset the carbon dioxide emissions from harvest and manufacturing. Partial harvests could allow for shorter rotation periods with similar effects on the carbon storage of the forest.

7. Jones, D. A., & O'Hara, K. L. (2016). **The influence of preparation method on measured carbon fractions in tree tissues.** *Tree Physiology,* 36(9), 1177–1189. http://doi.org/10.1093/treephys/tpw051

**Summary**
Study comparing the influence of carbon measurement method on the resulting percentage of carbon in tree tissues. Four methods were compared: oven-drying, vacuum desiccation, freeze-drying, and a new "minimize the loss of carbon method." The "minimize loss of carbon method" results in carbon percentages approximately 1.4% greater than the compared methods.

8. Jones, D. A., & O'Hara, K. L. (2018). **Variation in carbon fraction, density, and carbon density in conifer tree tissues.** *Forests*, 1–19. http://doi.org/10.3390/f9070430

**Summary**
Assessment of wood density and carbon content in nine conifer species. Accuracy of wood carbon estimates can be improved by with a carbon model that takes into account the variation in wood density and carbon content as a function of tree size.

9. Lamlom, S. H., & Savidge, R. A. (2003). **A reassessment of carbon content in wood: variation within and between 41 North American species.** *Biomass and Bioenergy*, 25(4), 381–388. http://doi.org/10.1016/S0961-9534(03)00033-3

**Summary**
Assessment of carbon content of 41 North American wood species. Past carbon calculations, due to calculation methods, omit volatile carbon content, underestimating total carbon content of wood in the forest. Additionally, carbon content between species and within individual trees can vary widely.

10. Major, J. E., Johnsen, K. H., Barsi, D. C., Campbell, M., & Malcolm, J. W. (2013). **Stem biomass, C and N partitioning and growth efficiency of mature pedigreed black spruce on both a wet and a dry site.** *Forest Ecology and Management*, 310(October 2017), 495–507. http://doi.org/10.1016/j.foreco.2013.08.019

**Summary**
Assessment of carbon content and biomass composition for black spruce trees on a wet and dry site. Wood density and wood composition varied between trees and sites. Overall stem volume was 23% greater on the wet site versus the dry site, but wood carbon content was consistent across sites, at 53.93%.

11. Mendell, B., & Lang, A. H. (2012). ***Comparing forest certification standards in the U.S., Part I: How are they being implemented today?*** The American Consumer Institute Center for Citizen Research. Washington, DC. Retrieved from http://www.theamericanconsumer.org/wp-content/uploads/2012/12/Comparing-Certification-Standards.pdf

**Summary**
Comparison of the guidelines and implementation of primary forest certification systems in the United States: American Tree Farm System (ATFS), the Forest Stewardship Council (FSC) and the Sustainable Forestry Initiative (SFI). In the past decades, FSC has relaxed some of its standards in response to business concerns, while SFI has tightened some standards in response to environmental concerns. All programs have similar requirements for chemical use and vegetation near streams. Central differences between programs are permissible harvest size and separation between adjacent stands. All programs exhibit significant variation in the application of their guidelines across regions.

12. Oliver, C. D., Nassar, N. T., Lippke, B. R., & McCarter, J. B. (2014). **Carbon, fossil fuel, and biodiversity mitigation with wood and forests**. *Journal of Sustainable Forestry*, 33(3), 248–275. https://doi.org/10.1080/10549811.2013.839386

**Summary**
Comparison of $CO_2$ and fossil fuel savings from harvested products and/or wood energy and the standing forest; and calculations of whether or not there is enough harvestable wood to make an impact on $CO_2$ emissions. They also examine what potential effect increased wood usage would have on biodiversity. The world has enough forest capacity to reduce annual $CO_2$ emissions by 14% to 31% and fossil consumption by 12% to 19%. The forest wood growth required would be 34% to 100%. Use of high efficiency wood products, such as wood I-joists, requires less forest use compared to products deemed lower efficiency (due to the amount of wood they use), such as CLT.

13. Prescott, C. E. (2009). **Litter decomposition: what controls it and how can we alter it to sequester more carbon in forest soils?** *Biogeochemistry,* 101(1), 133–149. http://doi.org/10.1007/sl0533-010-9439-0


**Summary**
Literature review by a faculty member at the University of British Columbia. Summarizes existing research on litter (decaying plant material such as leaves) decomposition and the related carbon sequestration in the soil. To sequester more carbon in soil, forestry management should promote microbial and chemical decomposition reactions that divert more litter into humus. Increasing soil nitrogen content through fertilization and nitrogen-fixing plants is identified as a successful method for increasing sequestration of carbon in soil.


14. Ranius, T., Hämäläinen, A., Egnell, G., Olsson, B., Eklöf, K., Stendahl, J., ... Felton, A. (2018). **The effects of logging residue extraction for energy on ecosystem services and biodiversity: A synthesis.** *Journal of Environmental Management*, 209, 409–425. http://doi.org/10.1016/j.jenvman.2017.12.048


**Summary**
Synthesis of studies on the effects of slash extraction on the forest ecosystem. Most evidence suggests that logging residue (slash) extraction can negatively impact forest biodiversity, for the remains of dead wood mimics large-scale natural forest disturbances. Slash extraction may also reduce future growth and carbon storage potential of a forest stand.


15. Seymour, R. S., & Hunter, M. L. (1999). **Principles of ecological forestry**. In *Maintaining biodiversity in forest ecosystems*. Cambridge University Press.


**Summary**
Book chapter discussing how ecological forest management can promote increased biodiversity. Sensitive forest management can reestablish biodiversity for areas that have previously been disturbed by human influence. Nevertheless, sustainable forest practices must be followed, and some forest lands should be preserved as reserves.


16. Smyth, C. E., Stinson, G., Neilson, E., Lemprière, T. C., Hafer, M., Rampley, G. J., & Kurz, W. A. (2014). **Quantifying the biophysical climate change mitigation potential of Canada' s forest sector.** *Biogeosciences*, (11), 3515–3529. http://doi.org/10.5194/bg-11-3515-2014


**Summary**
A study calculating the mitigation potential of Canada's managed forests from 2015 (compared to a base case) using the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3), a harvested wood products (HWP) carbon model, and a calculation of substitution benefits from wood products and bioenergy. They compare seven forest management strategies and two harvested wood product strategies. The greatest mitigation potential came from the multi-pronged strategy of better utilization, harvesting less, and shifting harvested wood products from shorter-lived products to longer living products.

17. Thomas, S. C., & Martin, A. R. (2012). **Carbon content of tree tissues: A synthesis.** *Forests*, 3(2), 332–352. http://doi.org/10.3390/f3020332

**Summary**
Synthesis of carbon content calculations of stem wood of 253 species from 31 studies. Average wood carbon content is 41.9-51.6% in tropical species, 45.7-60.7% in subtropical/Mediterranean species, and 43.4-55.6% in temperate/boreal species. Average carbon content for conifer species is 50.8%, in contrast to an average carbon content of 47.7% for angiosperm species. Live wood in standing trees contains 1.3-2.5% more carbon than dried wood samples, due to volatile carbon coefficients.

## Category: Life Cycle Assessment (LCA)

Studies relating to life cycle analysis, carbon accounting, and environmental impacts, often with a focus on wood or other biogenic materials

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1. Athena. (2017). ***Whole-building LCA benchmarks: A methodology white paper.*** Retrieved from http://www.athenasmi.org/wp-content/uploads/2017/11/BuildingBenchmarkReport.pdf

   **Summary**
   A paper discussing proposed methods for benchmarking whole-building LCAs. In order to achieve measurable reductions of the embodied carbon of buildings, a baseline must exist for comparison. The authors propose starting with a database of building bills of materials, so that different whole-building LCA (WBLCA) softwares could be used for future WBLCA comparisons..

2. Bergman, R. D., & Bowe, S. A. (2007). **Environmental impact of producing hardwood lumber using life-cycle inventory.** *In Proceedings of the 10th International IUFRO Division 5, Wood Drying Conference* (pp. 1–7). Retrieved from https://www.fs.usda.gov/treesearch/pubs/31113

   **Summary**
   Life cycle inventory of production of hardwood lumber, with comparison to softwood lumber. Inefficient wood drying kilns can consume more than 1.5 times more energy than new, efficient kilns. Upgrading kilns and increasing the amount of time that wood is air dried can reduce the environmental impacts of wood products.

3. Bergman, R., Puettmann, M., Taylor, A., & Skog, K. E. (2014). **The Carbon impacts of wood products.** *Forest Products Journal*, 64(7–8), 220–231. http://doi.org/10.13073/FPJ-D-14-00047

   **Summary**
   Calculates $CO_2$ eq. emissions savings for wood products compared to typical non-wood alternatives, within the scope of cradle-to-production gate. For wood products, amount of carbon sequestered is subtracted from $CO_2$ emissions from harvesting, transport, and manufacturing. $CO_2$ emissions exclude biogenic carbon emissions (from wood used as energy source) during manufacturing under the assumption of sustainable forest management practices. For the eleven wood products compared to typical material alternatives, the per unit net $CO_2$ eq. emissions of the typical (non-wood) products was approximately 760% to 100% greater than the wood products.

4. Chen, C. X., Pierobon, F., & Ganguly, I. (2019). **Life cycle assessment (LCA) of cross-laminated timber (CLT) produced in western Washington: The role of logistics and wood species mix.** *Sustainability,* 11(1278). http://doi.org/10.3390/su11051278

**Summary**

A cradle-to-gate LCA of CLT produced in western Washington, at two hypothetical mills. The LCA finds that the environmental impacts of CLT panels are affected by transportation distances and wood species mix. The cradle-to-gate global warming potential of CLT can be reduced by up to 14% by choosing nearby lumber sources and lighter wood species such as Sitka spruce instead of Douglas-fir. The cradle-to-gate global warming potential ranged from 156.7 kg $CO_2$ eq / $m^3$ to 185.69 kg $CO_2$ eq / $m^3$, between lumber source locations and species scenarios.

5. Cherubini, F., Peters, G., Berntsen, T., Stromman, A. H., & Hertwich, E. (2011). **$CO_2$ emissions from biomass combustion for bioenergy : atmospheric decay and contribution to global warming**. *GCB Bioenergy*, 413–426. http://doi.org/10.1111/j.1757-1707.2011.01102.x

**Summary**

A paper describing a method to calculate the climate impact of biogenic carbon emissions. In current practice, biogenic carbon emissions are typically assumed to be climate change neutral if the $CO_2$ released from biomass combustion approximately equals the amount of $CO_2$ sequestered in biomass (carbon flux neutral). Because this practice is inaccurate in its simplicity, the authors propose a calculation based on $CO_2$ impulse response functions (IRF) using atmospheric decay functions for biomass-derived $CO_2$ emissions. The metric produced by the model is $GWP_{bio}$, a measure of climate change impact as a function of biomass rotation periods. Although this paper only looks at biomass with a single rotation period, they further develop the model account for multiple rotation periods and management strategies in (Guest, Cherubini, & Strømman 2013).

6. Guest, G., Cherubini, F., & Strømman, A. H. (2013). **Global warming potential of carbon dioxide emissions from biomass stored in the anthroposphere and used for bioenergy at end of life.** *Journal of Industrial Ecology*, 17(1), 20–30. http://doi.org/10.1111/j.1530-9290.2012.00507.x

**Summary**

Analysis of methods and benefits of storing $CO_2$ in a material until burning for bioenergy at the end of life. A $GWP_{bio}$ factor can quantify how biogenic $CO_2$ emissions contribute to climate change relative to fossil $CO_2$ emissions, based on varying rotation and storage periods. Utilizing a $GWP_{bio}$ factor provides a more conservative view of carbon benefits (than presumed carbon neutrality) from bio-based materials. Longer storage periods provide the greatest carbon benefits. A simplified $GWP_{bio}$ factor could be applied to process LCAs to provide a more accurate understanding of carbon benefits.

7. Intergovernmental Panel on Climate Change. (2014). ***Climate change 2014 - Mitigation of climate change working group III contribution to the fifth assessment report of the Intergovernmental Panel on Climate Change***. Retrieved from https://www.ipcc.ch/report/ar5/wg3/

**Summary**
The Fifth Assessment Report (AR5) is a 2014 report from the Intergovernmental Panel on Climate Change (IPCC), assessing scientific, technical, and socio-economic information about climate change. The working group III section analyzes all options for mitigating climate change through limiting or preventing greenhouse gas emissions and removing them from the atmosphere. To avoid 2 degrees C (3.6 degrees F) of warming relative to preindustrial time, atmospheric concentrations of greenhouse gases need to stabilize around 450 ppm $CO_2$ eq or lower, although they were around 430 ppm $CO_2$ eq in 2014.

8. Liu, W., Zhang, Z., Xie, X., Yu, Z., von Gadow, K., Xu, J., … Yang, Y. (2017). **Analysis of the global warming potential of biogenic CO2 emission in life cycle assessments.** *Scientific Reports,* 7(July 2016), 39857. http://doi.org/10.1038/srep39857

**Summary**
Concise overview of biogenic carbon and case studies of the effect of a $GWP_{bio}$ factor on cradle-to-gate assessments of five different biofuel products. Utilizing a $GWP_{bio}$ factor increases estimations of GHG emissions for all five biofuels assessed. Shorter rotation lengths and higher mass lead to greater environmental benefits in this study. Authors caution that $GWP_{bio}$ factors may currently overestimate benefits, because negative impacts from natural disturbances (fire, drought, and insects) and climate change are not included

9. Lützkendorf, T., & Balouktsi, M. (2016). ***IEA EBC Annex 57 - Subtask 1: Basics, Actors and Concepts. Tokyo, Japan: Institute for Building Environment and Energy Conservation.*** Retrieved from http://www.iea-ebc.org/Data/publications/EBC_Annex_57_ST1_Basics_Actors_Concepts.pdf

**Summary**
Report findings from the project Annex 57 from the International Energy Agency. The goal of the Annex 57 part 1 is to identify and define fundamental concepts for embodied energy and embodied GHG emissions with respect to buildings.

10. Melton, P. (2018). **The urgency of embodied carbon and what you can do about it.** *Building Green.* Retrieved from https://www.buildinggreen.com/feature/urgency-embodied-carbon-and-what-you-can-do-about-it

**Summary**
Overview of embodied carbon, available LCA and WBLCA resources, and recommendations for professionals interested in reducing the embodied carbon of buildings or materials. To meet the goals of the Paris Agreement, fossil fuel emissions will need to be phased out by 2050. Professionals should focus on reducing embodied carbon emissions through re-purposing existing buildings, identifying (and reducing) embodied carbon hotspots, and performing whole building life cycle assessments. The article contains recommendations for reducing embodied carbon in concrete, steel, and timber materials.

11. Micales, J. A., & Skog, K. E. (1996). **The decomposition of forest products in landfills.** *International Biodeterioration & Biodegradation*, 39(2), 145–158. Retrieved from https://www.sciencedirect.com/science/article/pii/S0964830597833896

**Summary**
Research by the USDA Forest Service Forest Products Laboratory to understand the carbon decomposition of forest products to landfill gas in landfills.0-3% of the carbon in wood is emitted as landfill gas, with the remaining amount is generally permanently sequestered. Thus, landfilled wood products play a large role in the global carbon cycle.

12. Morris, J. (2016). **Recycle, bury, or burn wood waste biomass? Controls, displaced fuels, and impact costs**. *Journal of Industrial Ecology*, 21(4). http://doi.org/10.1111/jiec.12469

**Summary**
A hybrid life cycle assessment comparing different end-of-life options for wood waste from construction: recycle into another product, bury (in a landfill), or burn for bioenergy and replace fossil fuels. The options are compared for environmental costs on a 100 year time period after waste generation. The weighted impact categories are climate change, cancer risk, eco-toxicity, and human-induced environmental stress. Recycling was ultimately the best overall option, and landfilling was usually the next best option with the lowest impact, although the impact of landfilling was similar to that of burning for bioenergy.

13. Puettmann, M., Sinha, A., & Ganguly, I. (2018). ***CORRIM Report - Life cyle assessment of cross laminated timber produced in Oregon***. Retrieved from https://corrim.org/wp-content/uploads/2019/02/Life-Cycle-Assessment-of-Oregon-Cross-Laminated-Timber.pdf

**Summary**
This cradle-to-gate life cycle analysis document quantifies the environmental impacts of CLT made from douglas fir and larch lumber by the manufacturer DR Johnson in Riddle, Oregon. The data and methods follow the Product Category Rules (PCR) for North American Structural and Architectural Wood Products (FPInnovations 2015). D.R. Johnson CLT production data from the year 2016 is combined with previously published data for gate-to-gate softwood lumber production and cradle-to-gate forest resources. This CLT uses a melamine formaldehyde resin. In accordance with the PCR, biogenic $CO_2$ emissions from wood biomass burned during production are excluded from global warming potential (GWP). However, methane and nitrogen oxides from biogenic sources are included in GWP and other environmental impacts.

14. Sadler, P., & Robson, D. (2013). ***Carbon sequestration by buildings.*** The Alliance For Sustainable Building Products. Retrieved from https://asbp.org.uk/resource-report/carbon-sequestration-within-buildings

**Summary**
Study to determine the carbon sequestration achieved by buildings in the United Kingdom. The report contains a review of estimated wood usage in the United Kingdom in 2005, estimates future wood usage and develops a model for wood and renewable material usage up to 2050. The study uses a stock-change approach of carbon accounting and includes decomposition and decay of wood products in landfills. Net carbon sequestration from renewable biogenic building materials could reach 10Mt$CO_2$ in 2020 and 22Mt$CO_2$ by 2050, helping to achieve over 80% of the UK target for emissions reductions in homes and communities.

15. Salazar, J., & Bergman, R. (2013). **Temporal considerations of carbon sequestration in LCA.** *Proceedings from the LCA XIII International Conference, 2050* (2011). http://doi.org/10.13140/RG.2.1.2219.7925

**Summary**
Presentation of a dynamic calculation approach normalizing $CO_2$ sequestration and emissions at different points in time, in order to formulate overall GWP impact at year zero. This is an alternative method to the typical IPCC GWP 100-year calculation method used in cradle-to-grave models, which assumes that all carbon flows occur at year zero. Net biogenic carbon sequestration amounts are greater in the proposed alternative method that includes the dynamic nature of carbon sequestration and emissions flows. The carbon sequestration in the dynamic model is anywhere from 10.9% to 19.1% greater than calculated by the typical model, with the exact percentage difference dependent on the product service life.

16. Searchinger, T., Hamburg, S., Melillo, J., Chameides, W., Havlik, P., Kammen, D., … Tilman, G. (2009). **Fixing a critical climate accounting error.** *Science*, 326(October), 527–529.

**Summary**
A discussion of the flaws related to the assumption of biogenic carbon neutrality, specifically with regard to the production of bioenergy. Per the Kyoto Protocol, $CO_2$ emissions from bioenergy is not counted when emitted from tailpipes and smokestacks, and emissions are also not counted from the harvest and growth of bioenergy.

17. Suttie, E., Hill, C., Sandin, G., Kutnar, A., Ganne-Chédeville, C., Lowres, F., & Dias, A. C. (2017). **Environmental assessment of bio-based building materials.** In D. Jones & C. Brischke (Eds.), *Performance of Bio-based Building Materials* (pp. 547–591). http://doi.org/10.1016/B978-0-08-100982-6.00009-4

**Summary**
A comprehensive reference for the generic life cycle stages of bio-based building materials, biogenic carbon sequestration issues, life cycle assessments, and sustainable economy definitions. Discusses various EPD and life cycle tools and suggests areas for improvement.

18. Tellnes, L. G. F., Ganne-Chedeville, C., Dias, A., Dolezal, F., Hill, C., & Escamilla, E. Z. (2017). **Comparative assessment for biogenic carbon accounting methods in carbon footprint of products: A review study for construction materials based on forest products.** *IForest*. http://doi.org/10.3832/ifor2386-010

**Summary**
An overview of the methods of accounting for carbon sequestration in LCAs and proposed improvements. LCAs methods currently do not consider the dynamic nature of carbon sequestration or delayed emissions. However, many methods propose to include carbon flow timing in LCAs, but there is no consensus on these new proposed methods. Although the methods require additional data, the authors recommend the adoption of more sophisticated biogenic carbon models into the standards, taking into account the species and rotation period of wood or biogenic material

19. Wang, X., Padgett, J. M., De La Cruz, F. B., & Barlaz, M. A. (2011). **Wood biodegradation in laboratory-scale landfills.** *Environmental Science and Technology*, 45(16), 6864–6871. http://doi.org/10.1021/es201241g

**Summary**
Analysis by a research team from North Carolina State University, looking at the biodegradation of wood products in landfills. `Wood species have unique methane yields. Of the hardwood and softwood woods analyzed, the percentage of organic carbon that was converted to landfill gas ranged from 0 to 19.9% — considerably lower than IPPC recommended values.

20. US EPA. (2019). ***Methane emissions from landfills.*** Retrieved May 1, 2019, from https://www.epa.gov/lmop/basic-information-about-landfill-gas

**Summary**
General introduction to methane emissions and treatment in landfills in the United States. Gas generated in landfills is approximately 50% methane and 50% $CO_2$. Landfill gas is removed through a series of wells and a flare system before processing. After processing, the gas is used to generate electricity in approximately 72% of landfill gas recovery projects, while approximately 18% of projects use the landfill gas to offset the use of natural gas or fuel oil.

## Category: LCA - Standards and Product Declarations

Environmental standards and published documents for life cycle analysis.

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1. CEN. (2011). ***EN 15978 - Sustainability of construction works — Assessment of environmental performance of buildings — Calculation method***. http://doi.org/Ref. No. EN 15978:2011

**Summary**
European technical standard for performing a whole building life cycle assessment.

2. CEN. (2013). ***EN 15804:2013+A1 - Sustainability of construction works — Environmental product declarations — Core rules for the product category of construction products.***

**Summary**
European technical standard for product category rules for environmental product standards for construction products.

3. CEN. (2014). ***EN 16449: 2014 Wood and wood-based products - calculation of the biogenic carbon content of wood and conversion to carbon dioxide.***

**Summary**
European technical standard for the calculation method for accounting for biogenic carbon stored in wood products, to be referenced within product category rules. The equation requires input values for biogenic carbon content, wood volume, density, and moisture content:

4. CEN. (2014). ***EN 16485:2014. Round and sawn timber. Environmental product declarations. Product category rules for wood and wood-based products for use in construction.*** European Committee for Standardization, Brussels, Belgium.

**Summary**
European technical standard for product category rules for wood products used in construction. Referenced by other product category rules for the methodologies of accounting for biogenic carbon. For a sustainably-managed forest (forests in countries following article 3.4 of the Kyoto Protocol or forests with established certification schemes for sustainable forest management), overall contribution of biogenic carbon to global warming potential over the product life cycle is zero. Also, overall biogenic carbon balance over the product life cycle is zero.

5. FPInnovations. (2013). ***Environmental product declaration CrossLam by Structurlam.*** Retrieved from https://fpinnovations.ca/ResearchProgram/environment-sustainability/epd-program/Documents/environmental-product-declaration-structurlam-crosslam.pdf

**Summary**
2013 environmental product declaration for Structurlam's CrossLam CLT, produced in Okanagan Falls, BC, Canada.

6. FPInnovations. (2013). ***Environmental product declaration: Nordic X-Lam.***

**Summary**
2013 environmental product declaration for Nordic's X-lam CLT, produced in Chibougamau, Quebec, Canada.

7. FPInnovations. (2015). ***Product category rules for North American structural and architectural wood products.*** Retrieved from https://fpinnovations.ca/ResearchProgram/environment-sustainability/epd-program/Documents/pcr-v2.pdf

**Summary**
Product category rules for environmental product declarations for wood products, such as CLT, produced in North America. This PCR complies with ISO 21930: 2007, ISO 14025: 2006, ISO 14044:2006, and ISO 14040. This PCR is used by Structurlam's CLT EPD. Treatment of biogenic carbon storage and emissions aligns with EN 16485, except for in cradle-to-gate (business-to-business) LCA, where they are to be excluded.

8. FPInnovations Canada. (2018). ***Nordic X-Lam (CLT) environmental product declaration.*** Retrieved from https://fpinnovations.ca/ResearchProgram/environment-sustainability/epd-program/Documents/environmental-product-declaration-nordic-x-lam.pdf

**Summary**
2018 environmental product declaration for Nordic's X-lam CLT, produced in Chibougamau, Quebec, Canada.

9. ISO. (2006a). ***ISO 14025:2006. Environmental labels and declarations—Type III environmental declarations—Principles and procedures.*** International Organization for Standardization, Geneva, Switzerland

**Summary**
An internationally-recognized reference standard providing principles and definitions for type III environmental declarations (and product category rules), which are environmental declarations typically intended for business-to-business communication (although they may be used in business-to-consumer communication).

10. ISO. (2006b). ***International Standard ISO 14044:2006 Environmental management - Life cycle assessment - Requirements and guidelines.*** International Organization for Standardization, Geneva, Switzerland

**Summary**
An international reference standard of principles and definitions for the life cycle inventory process (LCI) and life cycle assessment studies (LCA).

11. ISO. (2018). ***International Standard ISO 14067:2018 Greenhouse gases - Carbon footprint of products - Requirements & guidelines for quantification.*** International Organization for Standardization, Geneva, Switzerland.

**Summary**
An international standard for quantifying the carbon footprint (also referred to as embodied carbon) of products. The standard specifies that the timing of emissions (i.e. dynamic carbon accounting) shall not be used for the calculation of global warming potential, although the effects of timing on emissions can be reported in a separate section of an EPD or LCA. The standard also affirms biogenic carbon neutrality except for biomass emissions to methane (and other non-$CO_2$ greenhouse gases).

## Category: Mass Timber

Information about mass timber products such as DLT and NLT.

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1. Binational Softwood Lumber Council. (2017). ***Nail-laminated timber design and construction guide. Binational Softwood Lumber Council.*** Retrieved from http://thinkwood.wpengine.com/wp-content/uploads/2018/01/reThink-Wood_Nail-Laminated_Timber_USDesignandConstructionGuide.pdf

   **Summary**
   Comprehensive overview of NLT. In addition to a history and description of NLT, it provides design and technical (structural, fire, environmental, and construction) guidance in eight chapters.

2. Busta, H. (2017, May 24). **Deep dive: mass timber 101: understanding the emerging building type.** Retrieved November 11, 2018, from https://www. constructiondive.com/news/mass-timber-101-understanding-the-emerging-building-type/443476/

   **Summary**
   An interview with Andrew Tsay Jacobs, director of the Building Technology Lab at Perkins+Will and a member of the International Code Council 's Ad Hoc Committee on Tall Wood Buildings Jacobs describes mass timber's current status in relation to building code. Authorities require significant testing to verify that designed mass timber wall assemblies will meet fire resistance requirements, but pending code changes should hasten approval for mass timber buildings. Mass timber seems to be most feasible for mid-rise projects where the aesthetic of exposed wood can fetch a market premium. Jacobs anticipates that wood, dowel-connected mass timber products will rise in popularity in the future.

3. Epp, L. (2018). **Dowel laminated timber.** *Wood Design & Building*. Retrieved from http://www.wooddesignandbuilding.com/dowel-laminated-timber/

   **Summary**
   An article by Lucas Epp, a leading structural engineer for timber buildings. The article covers the history, structural characteristics, and usage of dowel laminated timber.

4. reThink Wood. (n.d.). ***Mass timber in North America.*** Retrieved October 20, 2018 from https://www.awc.org/pdf/education/des/ReThinkMag-DES610A-MassTimberinNorthAmerica-161031.pdf

   **Summary**
   Continuing education presentation about mass timber in North America. Reviews the benefits of mass timber, describes the different types of mass timber, and suggests optimal applications.

5. Smith, R. E., Griffin, G., & Rice, T. (2015). ***Solid timber construction: process, practice, performance.*** Retrieved from https://cdn.ymaws.com/www.nibs.org/resource/resmgr/OSCC/OffSite_Studies_STC.pdf

**Summary**
Quantitative and qualitative analysis of the construction of eighteen mass timber projects around the world to understand benefits and challenges. The average reduction in construction time (compared to equivalent traditional construction) is 20% for buildings constructed with mass timber. For mass timber construction, there is also an average 4% cost savings, although some projects are more expensive than traditional methods. Key advantages of mass timber construction are speed, weather versatility, environmental benefit, decreased labor costs, lower weight, increased precision, safety. Key disadvantages are lack of knowledge/labor, logistical unfamiliarity, research, acoustic issues, job displacement, wind, code & permits, lack of component flexibility.

6. StructureCraft. (2017). ***Dowel laminated timber: mass timber design guide.*** Retrieved from https://structurecraft.com/materials/mass-timber/dlt- dowel-laminated-timber

**Summary**
General overview and design guide for dowel-laminated timber. The document contains history, performance properties, fabrication and installation information.

7. StructureCraft. (n.d.). ***Nail laminated timber – NLT.*** Retrieved March 5, 2019, from https://structurecraft.com/materials/mass-timber/nail-laminated-timber

**Summary**
Product information about StructureCraft's nail laminated timber panel product.

## Category: Synthesis - Literature Review

Literature reviews and studies analyzing existing available research in a general category

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1. De Wolf, C. (2017). ***Low carbon pathways for structural design: embodied life cycle impacts of building structures.*** Massachusetts Institute of Technology. Retrieved from https://dspace.mit.edu/handle/1721.1/111491

   **Summary**
   A thesis consisting of a meta-analysis of the embodied carbon of buildings and their structural systems. Well-designed buildings can potentially achieve an embodied carbon as low as 30 kg $CO_2$ eq./sm. Choice of low-carbon materials and maximizing structural efficiency are best ways to reduce building's embodied carbon.

2. Fain, S. J., Kittler, B., & Chowyuk, A. (2018). **Managing moist forests of the Pacific Northwest United States for climate positive outcomes.** *Forests*, 618(9), 1–20. http://doi.org/10.3390/f9100618

   **Summary**
   A literature review and synthesis of forest carbon life cycle assessments for the Pacific Northwest region. The review explains and analyzes different methodologies and assumptions, and how they affect the results. They conclude with recommended strategies to maximize the carbon storage potential of Pacific Northwest forests: extending harvest rotations, partial harvests, and managing forests for increased structural, age, and species complexity. To determine a climate-positive management plan, a full carbon analysis must extend beyond the forest to include the carbon pool of harvested wood products (with substitution and leakage effects).

3. Sathre, R., & O'Connor, J. (2010). ***A Synthesis of research on wood products & greenhouse gas impacts.*** Retrieved from http://lnu.diva-portal.org/smash/record.jsf?pid=diva2:455221

   **Summary**
   Annotated bibliography and review of studies about the net life cycle greenhouse gas impacts of wood products. A meta-analysis provides average displacement/substitution factors, indicating the average percentage reduction of greenhouse gas emissions as a result of using wood products instead in place of non-wood alternatives. Noted methodological challenges are the identification of a functional unit and variance in system boundaries for time and place. Most studies indicate that use of wood products reduces overall greenhouse gas emissions. End-of-life impacts are the most significant contributor to the overall greenhouse gas impact of wood products. Wood products should be sourced from sustainably-managed forests in order to reduce greenhouse gas emissions.

4. Miller, T. R., Gregory, J., & Kirchain, R. (2016). ***Critical issues when comparing whole building & building product environmental performance.*** MIT Concrete Sustainability Hub. Retrieved from http://hdl.handle.net/1721.1/104838

   **Summary**
   Discussion of issues affecting comparability and quality of whole building life cycle assessment comparisons. Whole building environmental performance cannot be adequately compared without identical system boundaries and analytical approaches. Key opportunities to improve individual whole building environmental declarations (whole building life cycle assessments) include: inclusion of typically-excluded modules (use, repair, etc.), improved reference study periods, uncertainty analysis, operational energy, and complex biogenic carbon models. Improved product category rules for assessing performance of the whole building would aid in standardization and comparability.

5. Nyrud, A. Q., & Bringslimark, T. (2010). **Is interior wood use psychologically beneficial? A review of psychological responses towards wood.** *Wood and Fiber Science*, 42(2), 202–218.

   **Summary**
   A literature review of psychological responses to interior wood use. The authors group the studies into perception of wood, attitudes towards wood products, and psychophysiological responses toward wood. Although most studies suggest that interior wood use has psychological benefit, the authors caution against any certainty in this conclusion.

6. Patel-Weynand, T. (2002). ***Biodiversity and sustainable forestry: state of the science review biodiversity and sustainable forestry: state of the science review***. Washington, DC: The National Commission on Science for Sustainable Forestry. Retrieved from http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.175.334&rep=rep1&type=pdf

   **Summary**
   Review of research on forest biodiversity. Biodiversity is integral to healthy and productive ecosystems, and the report identifies several key knowledge gaps in the understanding and communicating of biodiversity issues. Pertinent issues impacted by forest management are riparian buffers, harvest rotation periods, fragmentation effects, and below-ground ecosystem processes.

7. Simonen, K. (PI), Rodriguez, B., Barrera, S., McDade, E., & Strain, L. (2016). ***Embodied carbon benchmark study: LCA for low carbon construction.*** Retrieved from http://hdl.handle.net/1773/38017

**Summary**
A collection of existing whole building embodied carbon studies of buildings in order to determine suitable methods for benchmarking embodied carbon. The synthesis is based on a database of the embodied carbon of over 1,000 buildings, and contains discussion of key issues, including lack of comparability and data uncertainty. Data variances include different LCA boundaries, different LCA data, and different LCA methods. The data suggest several conclusions with inherent uncertainties due to inconsistent data. The initial embodied carbon of a building's structure, foundation, and enclosure is usually less than 1,000 kg $CO_2$ eq /sm, and the initial embodied carbon of commercial office buildings (structure, foundation, and enclosure) is between 200 and 500 kg $CO_2$ eq /sm for 50% of buildings identified.

**Category: User Guides**
Informational guides for WBLCA tools, carbon calculators, and building certification programs.

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1. Athena Sustainable Materials Institute; (2016). ***User manual and transparency document: impact estimator for buildings v.5*** (December 2016). Retrieved October 13, 2018, from https://calculatelca.com/wp-content/uploads/2017/02/IE4B_v5.2_User_Guide_December_2016.pdf

**Summary**
Explanation of the methodology and databases used in the Impact Estimator for Buildings (IE4B), a tool to conduct a life cycle assessment for buildings (WBLCA) located within the United States or Canada. In additional to calculating the embodied carbon impacts of the building, operational environmental impacts can optionally be assessed.

2. Bare, J. (2012). ***Tool for the reduction and assessment of chemical and other environmental impacts (TRACI) TRACI version 2.1 user's Guide***. US EPA Office of Research and Development.

**Summary**
User guide for TRACI version 2.1, an environmental impact assessment methodology used in life cycle assessment, primarily in the United States. The methodology defines midpoint impact categories: ozone depletion, global climate (global warming potential), acidification, eutrophication, smog formation, human health particulate, human health cancer, human health noncancer, and ecotoxicity.

3. FPInnovations. ***Carbon sequestration tool: background and user guide.*** Retrieved from https://fpinnovations.ca/ResearchProgram/environment-sustainability/epd-program/Documents/carbon-tool-user-guide-2.18.pdf

**Summary**
Guidelines and background on using FPInnovations' proprietary carbon sequestration tool to calculate the stored carbon values for use in LCAs and EPDs. Also provides guidance on general practices when accounting for biogenic carbon. Carbon sequestration can only be counted against GWP when sustainable forest harvest practices are followed. Biogenic carbon emissions may also be assumed to be carbon neutral, depending on the scope of analysis.

4. Living Building Challenge. (2014). ***Living Building Challenge 3.1: A Visionary Path to a Regenerative Future.*** Retrieved from http://living-future.org/ sites/default/files/reports/FINAL LBC 3_0_WebOptimized_low.pdf

**Summary**
A document outline the Living Building Challenge philosophy and program, describing the seven "petals," performance categories that a building must address. These categories are place, water, energy, health & happiness, materials, equity and beauty.

5. USGBC. (2013). ***Leed V4 User Guide.*** Retrieved from https://www.usgbc.org/resources/leed-v4-user-guide

**Summary**
User guide for achieving LEED certification under V4. The guide explains the LEED system and credit requirements. Key credits that CLT may influence are "Building life-cycle impact reduction: Whole-building life-cycle assessment" and "Building product disclosure and optimization - environmental product declarations."

6. WoodWorks Wood Products Council. (n.d.). ***Carbon calculator: references & notes.*** Retrieved September 27, 2018, from http://cc.woodworks.org/

**Summary**
Background methodology for WoodWork's carbon calculator. Key sources and assumptions for the calculator include: 50% wood carbon content by weight, general displacement (substitution) factors from Sathre & O'Connor (2010), and harvest efficiency assumption of 90% (with 10% remaining in the forest, based on a Metafore (2006) study. For CLT and other mass timber products, the calculator uses a specific mass timber displacement factor of .71. Forest growth rate calculations are based on information from the USDA.

7. US EPA. (2016). ***Documentation for greenhouse gas emission and energy factors used in the waste reduction model (WARM) construction and demolition materials chapters.*** Retrieved from https://www.epa.gov/sites/production/files/2016-03/documents/warm_v14_construction_demolition_materials.pdf

**Summary**
Report of the methodologies and assumptions used to model the end-of-life environmental impacts of construction materials in the WARM tool provided by the Environmental Protection Agency, an United States Government Agency. WARM divides construction waste into various categories; the wood products category contains two subcategories of dimensional lumber and medium density fiberboard (MDF). At this time, it does not differentiate between mass timber products such as CLT. For wood products, WARM can model three different end-of-life scenarios: recycling, combustion, and landfilling.