

### Executive Summary

This Cross-Laminated Timber (CLT) Info Sheet series provides a general overview of cross-laminated timber in buildings, relevant design information, and a synthesis of research on embodied and stored carbon of CLT.

After an extensive literature review of resources drawn primarily from current studies in Canada and the United States, themes (and questions) emerged, and it became evident that there are gaps in knowledge of CLT's usage and environmental impacts. This info sheet series partially addresses this gap with topics ranging from general to specific and is intended to serve as an educational resource for students, professionals, and CLT project stakeholders. References for each info sheet are listed at the end of each sheet and in the annotated bibliography, which includes sources of peer-reviewed journal articles, industry, professional practice, research from universities and institutes, standards, and environmental product declarations. 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 info sheets are organized into three sections: Background (info sheets #1-4), Design (info sheets #5-8), and Environmental Impacts (info sheets #9-18).

The Background section serves as a starting point for those unfamiliar with CLT. #1 "What is Cross-Laminated Timber?" defines essential terminology, history, manufacturing processes, and an overview of codes and standards. #2 "CLT in the United States & Canada" identifies North American CLT building and manufacturing locations as well as the growth of the CLT market. #3 "Benefits of CLT" highlights the potential strengths of CLT as a construction material, from construction times to aesthetics to potential emissions reductions. #4 "CLT Innovations" describes several CLT variations and their capabilities.

The Design section provides considerations and information for designers and builders interested in using CLT. #5 "CLT and Building Code" examines current and future code standards in CLT construction. #6 "CLT, DLT, & NLT Comparison" compares the three common types of mass timber wood panels, including history, uses, sizing, code standards, and advantages and disadvantages of each. #7 "CLT & Certification Programs" addresses how using CLT might help achieve specific environmental certifications. #8 "Net-Zero Design with CLT" explains how CLT can help achieve a net zero building through thermal performance and airtightness.

The Environmental Impacts section discusses how embodied carbon and stored carbon might make CLT a renewable building material. These fact sheets address a technical, in-depth understanding of this topic. Additionally, this category presents several current knowledge gaps and recommendations about wood, carbon, CLT, and Life Cycle Assessments (LCAs). #9 "Intro to Life Cycle Assessment" provides a diagram and terminology used in the following sheets. #10 "CLT EPDs & Biogenic Carbon" describes how embodied carbon is calculated for CLT, how LCAs are completed for CLT, and defines biogenic carbon. #11 "Carbon Content of CLT" discusses how stored carbon is currently calculated for wood products, as well as the generalizations behind these calculations. #12 "CLT Life Cycle Analysis" diagrams the cradle-to-gate production of CLT and highlights example environmental impacts from North American CLT manufacturers. #13 "CLT Production Carbon Impacts" explains the carbon impacts of the production life cycle stages of CLT. #14 "End-of-Life CLT Carbon Impacts" dives into disposal practices for CLT, which has significant impacts on emissions calculations. #15 "Embodied Carbon of CLT Buildings" defines embodied carbon and highlights embodied carbon calculations for existing case study buildings. #16 "Reducing CO<sub>2</sub> Emissions from CLT" builds upon the previous info sheet, explaining opportunities for embodied carbon reduction. #17 "Wood & Carbon: Knowledge Gaps" discusses the current gaps in research and knowledge concerning wood and carbon sequestration, the role of forestry management practices, wood decomposition, and biodiversity implications. #18 "CLT & LCA: Knowledge Gaps" emphasizes the uncertainty and imprecision around life cycle assessments, specifically around the timing of emissions and the limitations of current LCA and WBLCA data.

CLT knowledge and implementation is evolving quickly, and the carbon and environmental impacts of CLT are not fully understood. CLT is not a "magic bullet" of building materials, and there is no consensus on many of the issues, particularly for those covered in the Environmental Impacts section. We guide the reader to info sheet #17 and #18 for information on current and expected areas of future research.

Are you unfamiliar with CLT?  
Start here!

### Background

- 1 What is Cross-Laminated Timber?
- 2 CLT in the United States & Canada
- 3 Benefits of CLT
- 4 CLT Innovations

Thinking of designing a  
building with CLT? These  
info sheets are for you!

### Design

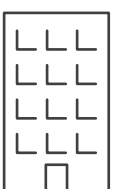
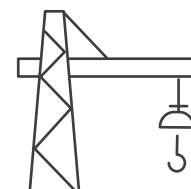
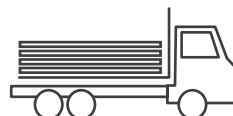
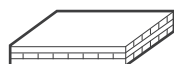
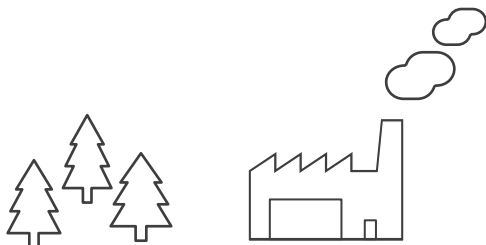
- 5 CLT and Building Code
- 6 CLT, DLT, & NLT Comparison
- 7 CLT & Certification Programs
- 8 Net-Zero Design with CLT

Are you curious  
about how embodied  
and stored carbon can  
make CLT a sustainable  
building material? Skip  
to these info sheets!

### Environmental Impacts

- 9 Intro to Life Cycle Assessment
- 10 CLT EPDs and Biogenic Carbon
- 11 Calculating Stored Carbon in CLT
- 12 CLT Life Cycle Analysis
- 13 CLT Production Carbon Impacts
- 14 End-of-Life on CLT Carbon Impacts
- 15 Embodied Carbon of CLT Buildings
- 16 Reducing Carbon Impacts of CLT
- 17 Wood & Carbon: Knowledge Gaps
- 18 CLT & LCA: Knowledge Gaps

### References



# What is Cross-Laminated Timber?

## Introduction

Cross-laminated timber, often referred to as CLT, is "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, 2017a, p. 60).

## History

CLT was invented in the early 1990s in central Europe (Karacabeyli & Brad, 2013). CLT is now a well-established building material in Europe and has been gaining worldwide popularity as CLT manufacturing facilities spread outside Europe in the 2010s (Grasser, 2015).

## Manufacturing Process

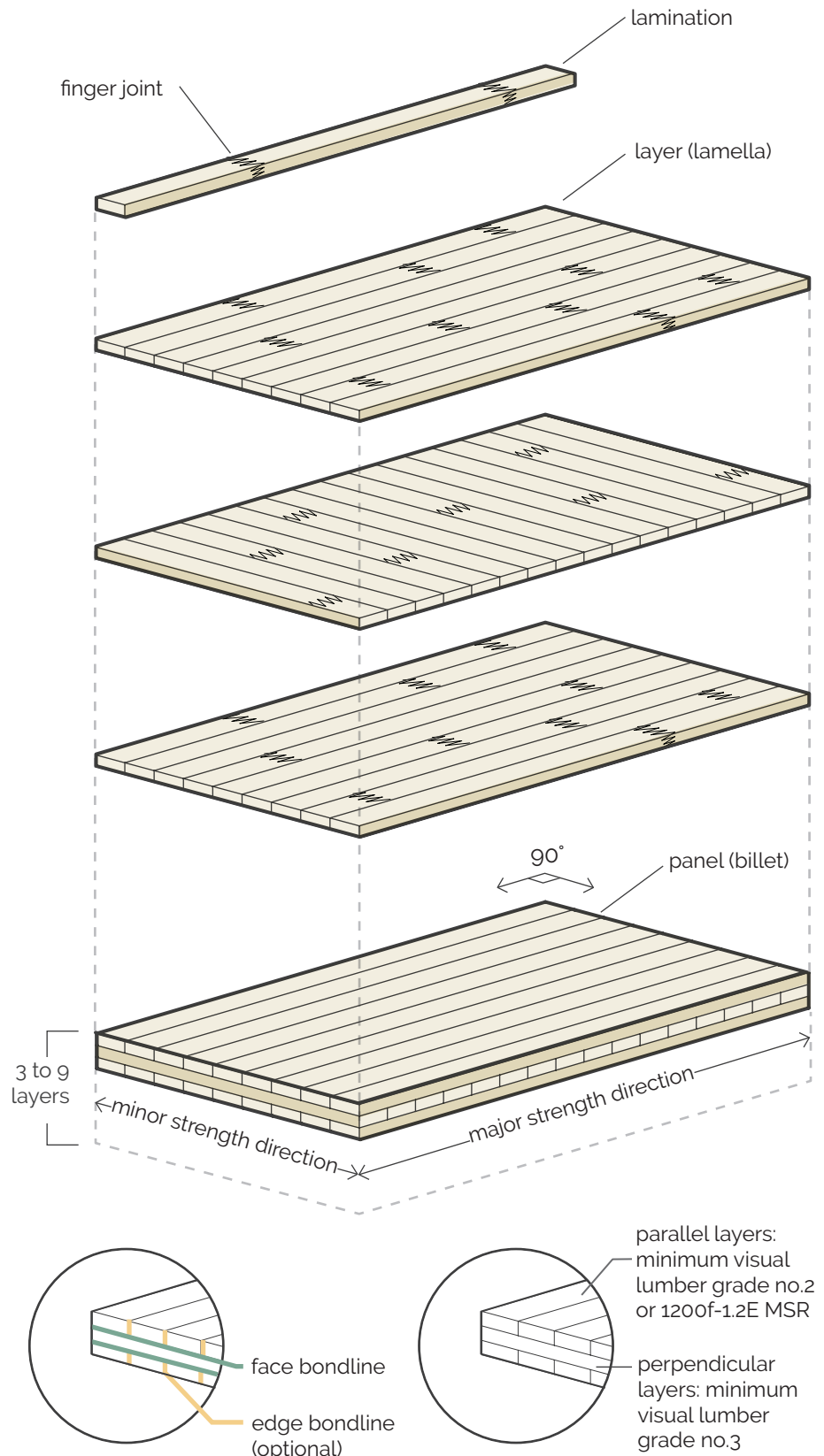
First, lumber is dried to a moisture content of approximately 12%. Lumber is then selected, grouped, planed, finger-jointed, and assembled into individual layers. Layers are oriented perpendicular to one another, glued together, and pressed in a vacuum or hydraulic press. After the panels are pressed, openings for doors and windows are cut in the panels, finishes or sealants can be applied, and the product is packaged (Karacabeyli & Brad, 2013, p. 25).

## Key Uses

CLT can be a structural or non-structural material, depending on the application. CLT is often used in walls, floors, walls, ceilings, stairs, and roofs.

## Code and Standards

The 2015 International Building Code allows for the use of CLT under prescriptive or performance-based approval paths. CLT used for prescriptive code approval must be certified according to the standards of ANSI/APA PRG 320-2018: Standard for performance-rated cross-laminated timber. The 2021 International Building Code will contain expanded code-approved options (Mayo et al., 2018).





# What is Cross-Laminated Timber?

## Terminology

### APA - The Engineered Wood Association

a nonprofit trade association of the United States and Canadian engineered wood products industry

### ANSI/APA PRG 320-2018: Standard for Performance-Rated Cross-Laminated Timber

This ANSI/APA performance standard provides definitions, requirements, and test methods for structural CLT. Standards encompass panel dimensions, dimensional tolerances, lumber properties, adhesives, performance criteria, and manufacturing plant requirements. Specifies product performance classes for CLT (APA, 2018).

### Billet

Synonymous with CLT panel (see below).

### CLT Panel

A CLT unit formed by bonding layers of laminations with a structural adhesive (APA, 2018, p. 3).

### Edge Bondline

The optional adhesive layer on the narrow faces of laminations within one layer (APA 2018, p. 3).

### Face Bondline

The adhesive layer between adjacent layers (lamellas) of a panel (APA, 2018, p. 3).

### Finger Joint

A joint composed of interlocking tapered points uniting shorter pieces of lumber.

### Layer

"An arrangement of laminations of the same thickness, grade, and species combination laid out essentially parallel to each other in one plane" (APA, 2018, p. 5).

### Lamination

"A piece of sawn lumber or structural composite lumber, [that is] prepared and qualified for laminating" (APA, 2018, p. 5).

### Lamella

A single layer of a CLT panel composed of lumber pieces (laminations) laminated together along their depth (Sutton, Black, and Walker, 2011).

### Minor Strength Direction

The direction perpendicular to the major strength direction of the CLT panel (APA, 2018, p. 3).

### Major Strength Direction

The general direction of the grain of the laminations in the outer layers of the CLT panel (APA, 2018, p. 3).

### MSR Lumber

Machine stress rated lumber is a type of machine-graded lumber. Lumber undergoes a nondestructive machine evaluation test followed by visual grading for aspects the machine cannot test (Kretschmann, Evans, & Green, 2010).

### Visual Lumber Grade

Visually graded lumber has been assessed for the presence of defects and other characteristics; based on the visual grade, the design properties of different species are specified in the standard National Design Specification (NDS) Supplement Design Values for Wood Construction (AWC, 2017b). Standard visual grades include Select Structural (best), No. 1, No. 2, and No. 3 (worst) (AWC, 2017b).

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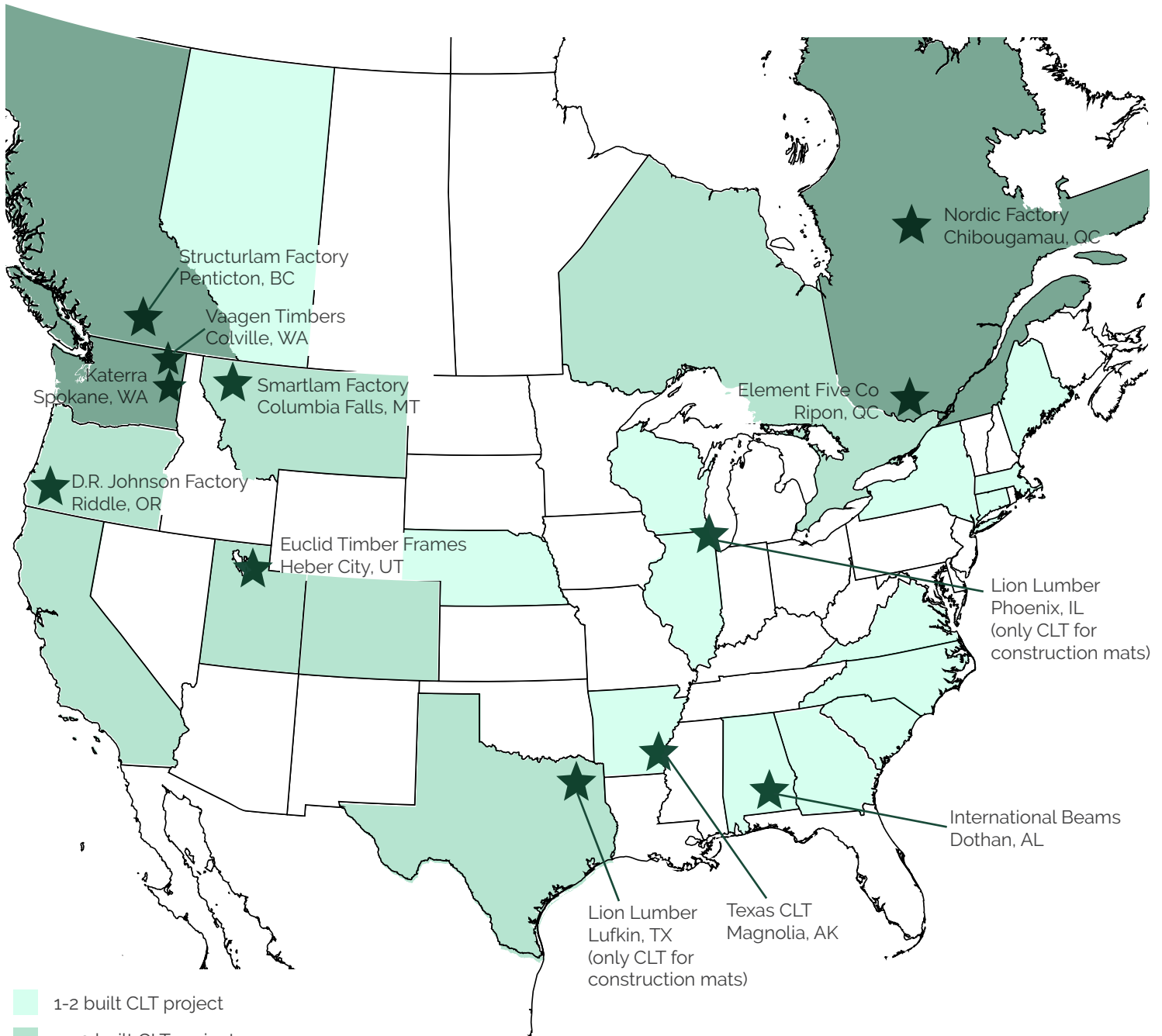
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Sutton, A., Black, D., & Walker, P. (2011). *Cross-laminated timber: an introduction to low-impact building materials*. Information Paper - IP17/11. Retrieved from the BRE website: [https://www.bre.co.uk/filelibrary/pdf/projects/low\\_impact\\_materials/IP17\\_11.pdf](https://www.bre.co.uk/filelibrary/pdf/projects/low_impact_materials/IP17_11.pdf)

# CLT in the United States & Canada

## Introduction

The use of CLT as a building material in the United States and Canada has been growing since the opening of North American manufacturing facilities in 2010 (Nordic), 2011 (Structurlam), and 2012 (Smartlam). The CLT market continues to expand in North America, and several new CLT factories are being built (Texas A&M Forest Service, 2018). The map of CLT buildings below is not exhaustive and will undoubtedly rapidly change in the future as more CLT buildings are constructed.



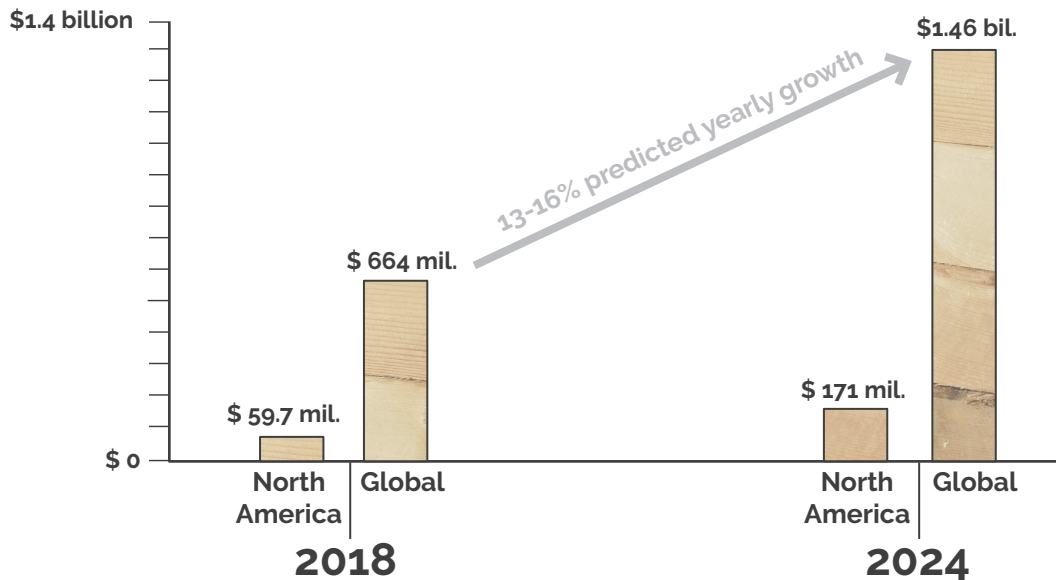
## Distribution of CLT Projects (built) & Manufacturers

\*Note: map is not exhaustive and does not include unpublished or uncompleted projects  
\*sources for CLT project information include manufacturer, industry, and news websites

# CLT in the United States & Canada

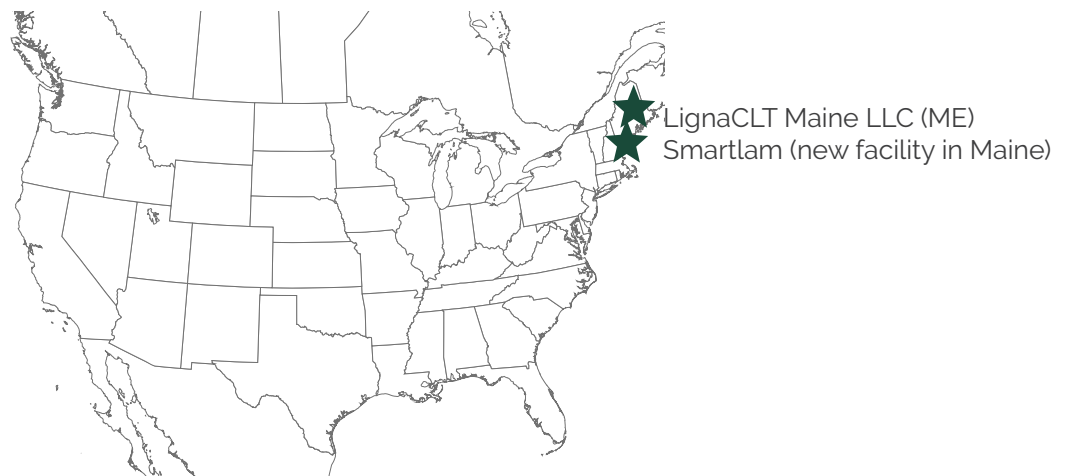
## Global and North American predicted CLT market value growth

\*Source: (Imarc Group, 2019a; 2019b)



## Future North American CLT manufacturing locations

\*Source: (Texas A&M Forest Service, 2018)



## Sources

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>

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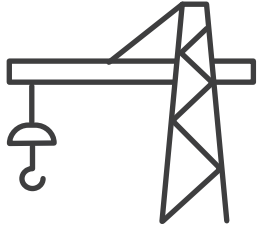
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# Benefits of CLT

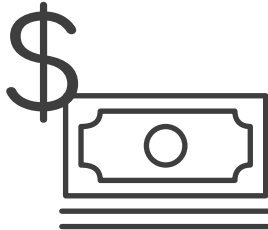
## Introduction

Cross-laminated timber has multiple strengths as a construction material that can supplement or substitute for steel and concrete construction. It can be a sustainable structural material with an efficient construction schedule and viable cost. There are many factors to consider when selecting the most suitable building material for a specific use.



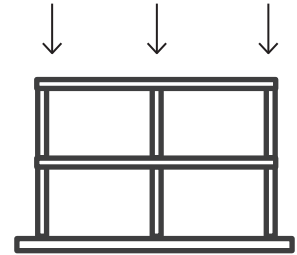
### Faster Construction

Because CLT panels offer a high level of prefabrication, CLT systems can reduce construction time by approximately 20% when compared to cast-in-place concrete systems. CLT panel construction, similar to other prefabricated systems (such as precast concrete or structural insulated panels), allows for precise, factory-cut openings for doors, windows, and mechanical elements (Waugh Thistleton Architects, 2018; Smith, Griffin, & Rice, 2015).



### Competitive Cost

Buildings using CLT can be cost-competitive with steel and concrete. Although construction project costs vary widely based on building type or design, CLT buildings can result in a cost savings (Mahlum, Walsh Construction Co., & Coughlin Porter Lundeen, 2014; Atlantic WoodWorks, 2016) or cost premium (Cary Kopczynski & Company, 2018). Insurance costs for CLT construction can be higher (Atlantic WoodWorks, 2016) but overall construction costs for CLT buildings are expected to decrease as familiarity with the material increases (Mahlum et al., 2014).



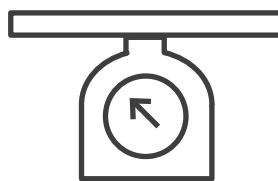
### Structural Performance

Due to the cross-lamination of layers, CLT exhibits relatively high in-plane and out-of-plane strength. The strength and cross-lamination make CLT capable of a two-way span, similar to reinforced concrete (Karacabeyli and Brad, 2013, p. 22). The use of CLT as the gravity-resisting structure is well-established and allowed in IBC 2015 (Mahlum et al., 2014). However, CLT's usage for lateral and seismic resistance currently requires an extensive performance-based code approval (Mahlum et al., 2014, p. 5); current research is defining a basis for lateral and seismic resistance in future building codes (Pei et al., 2014).



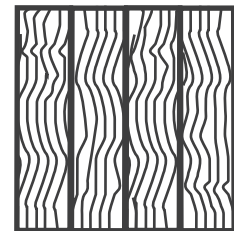
### Energy Efficient Assemblies

When coordinated with climate and ventilation strategies, CLT systems can help provide maximum energy efficiency. Studies simulating the operational energy of CLT residential buildings at multiple locations in China (Guo, Liu, Chang, Shao, & Sun, 2017) and at multiple locations in the United States (Khavari, Pei, Asce, & Tabares-Velasco, 2016) have demonstrated that CLT buildings can perform as well or better than comparable traditional residential building forms, although CLT may be best suited to colder climates.



### Light Weight Material

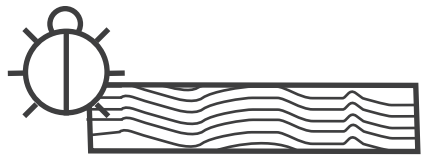
CLT systems typically lead to lower weight buildings than traditional construction systems, which has helped reduce foundation size on many projects in the United Kingdom (Waugh Thistleton Architects, 2018) and can potentially make it feasible to use smaller cranes during construction (Karacabeyli and Brad, 2013, p. 17). At an equivalent volume, CLT weighs approximately 20% of the weight of concrete (average strength).



### Natural Aesthetic of Wood

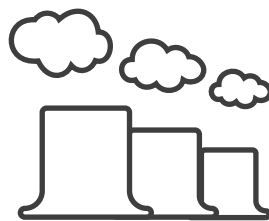
Exposing the natural wood finish of CLT in an interior space showcases the natural beauty of wood. Multiple studies suggest, but do not prove, potential psychological benefits from interior environments with visible wood (Nyrud & Bringslimark, 2010). A desire for the natural finish of CLT must be weighed against fire resistance needs; CLT may require additional fire protection covering the natural finish.

# Benefits of CLT



## Alternative Lumber Utilization

The CLT manufacturer, Structurlam, assembles ANSI/APA PRG 320-certified CLT panels that include some beetle-kill pine lumber (Alter, 2012). Another CLT manufacturer, Euclid Timber Frames, produces an interlocking CLT product with beetle-kill lumber (although interlocking CLT is not ANSI/APA PRG-320 certified) (Smith & Kretschmann, 2013). Researchers at Oregon State University are currently examining the feasibility of using reclaimed wood members in CLT panels (Portland Design, 2018). CLT can help provide a higher value product for alternative wood sources that typically merit disposal.



## May Reduce CO<sub>2</sub> Emissions

Using CLT and other wood construction materials instead of steel and concrete can result in lower CO<sub>2</sub> and other greenhouse gas emissions when considering the whole material life cycle (Gu & Bergman, 2018; Skullestad, Böhne, & Lohne, 2016). For more information, see info sheet #15. However, most studies assume that biogenic carbon is climate change neutral. Consequently, they exclude CO<sub>2</sub> emissions from forest residue (branches left to decompose during harvesting) and from burning wood during manufacturing of wood products. A study including these biogenic CO<sub>2</sub> emissions found that they increased overall CO<sub>2</sub> emissions from manufacturing by about 40% (Skullestad et al., 2016, p. 9). The same study found that a CLT building still had lower CO<sub>2</sub> emissions than a comparable reinforced concrete building, despite including biogenic carbon (Skullestad et al., 2016).



## Renewable Resource

Mass timber products, including CLT, can be considered a renewable resource if harvested from a sustainably-managed forest. Sustainable harvesting practices like waterway protections, increased green tree retention, and longer rotation periods can increase the carbon storage potential of a forest, compared to business-as-usual or state-mandated practices (Diaz, Loreno, Ettl, & Davies, 2018, p. 19). However, a full accounting of the greenhouse gas implications of these activities should also consider any change in the output of forest products from managed lands and the substitute products that may need to be produced in the economy to make up for this change in forest products (Smyth et al., 2014).

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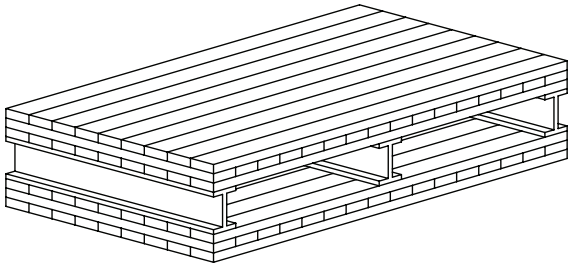
\*For remaining sources, see reference list.



# CLT Innovations

## Introduction

Most CLT manufacturers offer varying layer thicknesses, number of layers, and wood combinations. However, some manufacturers and researchers hope to expand CLT's performance capabilities through new connection methods and other innovations. Cassette panels, 45 degree CLT, and hardwood CLT aim to improve the structural performance of CLT. Interlocking and dowel-connected CLT styles use wood connections to join layers in lieu of adhesives, lessening the environmental impacts and volatile organic compound (VOC) emissions of the overall panel. Because these products cannot be certified by ANSI/APA PRG 320, they currently require a performance-based code approval path for most uses.



## Cassette Panels

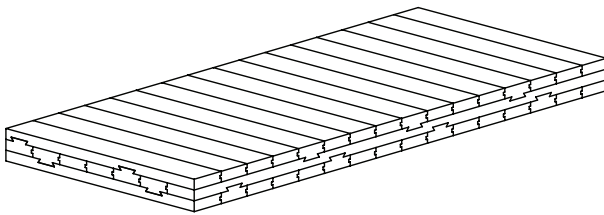
CLT panel layers sandwich an interior layer of structural members (such as joists, studs, or beams), with space for insulation, electrical, and mechanical systems. Prefabricated cassette panels typically contain wood structural members in the middle layer and can be used for floors, walls, or roofs (Element5 Co, n.d.).

### Advantages

- Supports floor spans of 10-12 m (normal CLT spans up to 9 m).
- Hollow cores allow for insulation, electrical and mechanical systems without the need for additional layers of enclosure.

### Manufacturers include (but are not limited to):

Element 5 Co. (Canada), Egoi (Spain), and Stora Enso (Sweden)



## Interlocking CLT (adhesive-free)

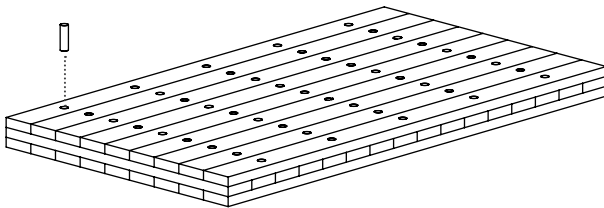
A CLT system that uses interlocking joints (tongue and groove and dovetail) or ribbed joints instead of fasteners and adhesives (Smith, 2011; Plackner, 2014).

### Advantages

- Avoids the use of adhesives and the environmental impacts associated with them.
- Allows for deconstruction of members and reuse at end of life.

### Manufacturers include (but are not limited to):

Euclid Timber Frames (Utah), Holzbau Bendler (Germany), Inholz (Germany), and Holzbau Binz (Germany)



## Dowel-Connected CLT & Nail-Connected CLT (adhesive-free)

CLT layers can be connected with wooden dowels or nails instead of adhesives (Muszynski, Hansen, Fernando, Schwarzmann, & Rainer, 2017, p. 90).

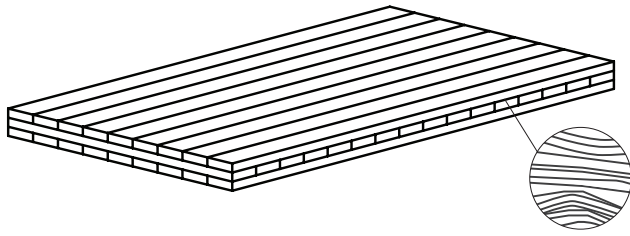
### Advantages

- Avoids the use of adhesives and the environmental impacts associated with them.

### Manufacturers include (but are not limited to):

Holz100 (Canada & Austria), International Timberframes (Canada), and other European manufacturers (Muszynski et al., 2017).

# CLT Innovations



## Hardwood CLT

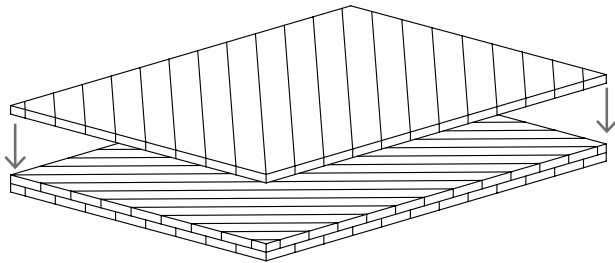
CLT with hardwood species for some or all layers (replacing the typical softwood species used in CLT) has been studied by several researchers (Aicher, Hirsch, & Christian, 2016; Erhart & Brandner, 2018). Currently, a collaborative team from the USDA Forest Products Laboratory and Michigan State University is investigating the use of low grade hardwood in CLT (USDA Forest Products Laboratory, n.d.).

### Advantages

- CLT with hardwood layers can improve stiffness and strength in rolling shear (Erhart & Brandner, 2018).

### Manufacturers include (but are not limited to):

Hasslacher (Austria)



## 45 degree CLT (under development)

Norwegian researchers have investigated turning transverse CLT layers at 45 degree angles instead of 90 degrees to achieve a stronger panel. Currently, they are looking at how to achieve the same amount of waste as within normal CLT (Buck, 2016).

### Advantages

- Performs better than typical CLT on several tested strength properties, including bending strength.

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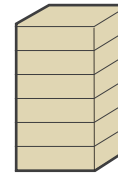
# CLT and Building Code

## Introduction

The 2015 International Building Code (IBC) incorporates requirements for CLT as type IV construction (heavy timber) under the prescriptive path for approval. Heavy timber (type IV) construction is "construction in which the exterior walls are of noncombustible materials and the interior building elements are of solid or laminated wood without concealed spaces" (International Code Council, 2015, p. 3). CLT can also be used in type III (combustible) construction or type V (wood frame) construction. Usage beyond the defined allowances requires approval via a performance-based path for code compliance.

However, the 2021 International Building Code will have expanded allowances and new building types for mass timber structures (Francis & Coats, 2018).

## current code 2015 IBC



maximum height  
85 ft / 6 stories

### Type IV

Mass timber is permitted to be exposed.

**Maximum Height :** 85 ft (26 m)

**Number of Stories:** ≤6

**Mass Timber:** Fully exposed

**Sprinklers:** Required

**Frame Fire Resistance:** varies

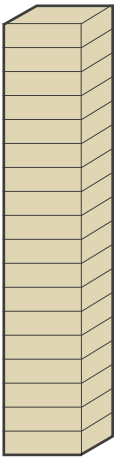
**Floor Fire Resistance:** varies

**Concealed Spaces:**

Permitted but must have protection

## 2021 IBC

\*type IV from the 2015 IBC becomes type IV-HT (heavy timber)



maximum height  
270 ft / 18 stories

### Type IV-A

Mass timber must be fully protected by noncombustible protection.

**Maximum Height :** 270 ft (82 m)

**Number of Stories:** ≤18

**Mass Timber:** Fully concealed

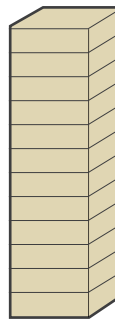
**Sprinklers:** Required

**Frame Fire Resistance:** 3 hours

**Floor Fire Resistance:** 2 hours

**Stair Enclosure:** Non-Combustible

**Concealed Spaces:** Permitted but must have protection



maximum height  
180 ft / 12 stories

### Type IV-B

Mass timber must be partially protected by noncombustible protection.

**Maximum Height :** 180 ft (55 m)

**Number of Stories:** ≤12

**Mass Timber:** Partially exposed

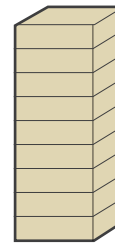
**Sprinklers:** Required

**Frame Fire Resistance:** 2 hours

**Floor Fire Resistance:** 2 hours

**Stair Enclosure :** Mass Timber

**Concealed Spaces:** Permitted but must have protection



maximum height  
85 ft / 9 stories

### Type IV-C

Mass timber is permitted to be exposed.

**Maximum Height :** 85 ft (26 m)

**Number of Stories:** ≤9

**Mass Timber:** Fully exposed

**Sprinklers:** Required

**Frame Fire Resistance:** 2 hours

**Floor Fire Resistance:** 2 hours

**Stair Enclosure :** Mass Timber

**Concealed Spaces:** Permitted but must have protection



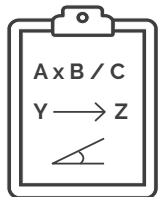
# CLT and Building Code

## Terminology



### Prescriptive Design / Code Compliance

In the prescriptive design path, a building is designed to meet the building code's span table and specific detailing requirements in order to create a code-compliant design. For instance, building type IV specifies required sizes and thickness of timber elements that will be fire-resistive. Getting approval through the prescriptive path is relatively fast and requires fewer additional calculations than the performance-based path (Woodworks Wood Products Council, 2018).



### Performance-Based (Engineered) Design / Code Compliance Path ("Alternative Method")

In the performance-based (engineered) path, the design team provides specific calculations showing that the structural design meets code. A design must meet the requirements of ASCE/SEI 7 and NDS for Wood Construction in addition to the International Building Code. ASCE/SEI 7 Minimum Design Loads for Buildings and Other Structures (ASCE 7) contains code-required loading and analysis methods for buildings. The National Design Specification (NDS) for Wood Construction contains code-referenced standards for the design of structural wood materials and connections. (WoodWorks Wood Products Council, 2018).

## 2021 Code Changes

In 2016, the interdisciplinary committee International Code Council (ICC) Tall Wood Building Ad Hoc Committee began formulating building code recommendations for tall wood buildings (Mayo et al., 2018). In 2018, the committee's proposals were approved for inclusion in the 2021 International Building Code (Locke, 2018).

In 2018, Oregon officials issued the Statewide Alternate Method (SAM) No. 18-01, providing a prescriptive path for utilization in Oregon of the code requirements developed by the International Code Council (ICC) Tall Wood Building Ad Hoc Committee, before these code sections become part of the 2021 IBC (Mayo et al., 2018). SAM allows for early technical consideration and approval on a statewide basis. Through a similar process, other states could adopt the recommendations prior to the 2021 IBC.

The key recommendations of the committee establish four sub-types for type IV construction that allow for taller mass timber buildings. Additionally, they require that mass timber CLT elements shall be tested and labeled for heat-performing adhesives (Francis & Coats, 2018).

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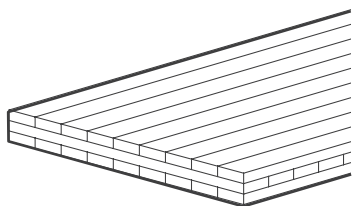
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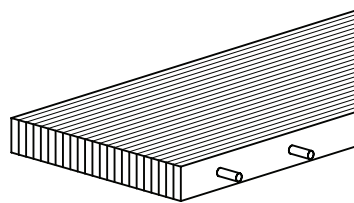
# CLT, DLT, & NLT Comparison

## Introduction

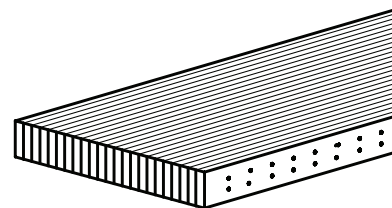
Cross-laminated timber (CLT), nail-laminated timber (NLT), dowel-laminated timber (DLT) are mass timber engineered wood panels with promising construction applications. They are typically prefabricated before transport to a construction site, and they can be used structurally or non-structurally. Some variations exist within these categories; for instance, CLT layers can be joined together with wood dowels or nails, similar to DLT or NLT.



**CLT**



**DLT**



**NLT**

## Description

CLT is an engineered wood product made of three or more layers of lumber, cross-oriented and bonded with adhesives (American Wood Council, 2017a, p. 60).

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

NLT is panel made of standard dimensional lumber pieces attached on edge with nails or screws to form a panel (ReThink Wood, 2018).

## History

CLT was invented in the early 1990s in Europe (Crespell & Gagnon, 2010). Usage of CLT continues to grow internationally.

DLT was developed in the 1990s in Switzerland as an alternative to NLT (Epp, 2018, p. 2). Without nails, DLT panels can be more easily field-cut than NLT panels.

NLT has been used for over 150 years in warehouse construction, but usage declined with the popularization of steel and concrete construction. NLT was reintroduced in Switzerland in the 1970s and 1980s (Epp, 2018, p. 2).

## Primary Uses

Structural: walls, floors, roofs  
Non-structural: walls

Structural: walls, floors, roofs, decks  
Non-structural: walls

Structural: walls, floors, roofs, decks  
Non-structural: walls

## Approximate Maximum Size

Maximum width: 13 ft (4.0 m)  
Maximum length: 80 ft (24.0 m)  
Maximum thickness: 20 in (508 mm)  
(Grasser, 2018)

Maximum width: 14 ft (4.3 m)  
Maximum length: 60 ft (18 m)  
Maximum thickness: 14 in (349 mm)  
(Structurecraft, 2017)

Maximum width: 12 ft (3.6 m)  
Maximum length: 100 ft (30.5 m)  
Maximum thickness: 12 in (305 mm)  
(Structurecraft, n.d.)

## Building Code

In the 2015 International Building Code (IBC), CLT qualifies as a prescriptive heavy timber assembly in Type IV construction when manufactured according to the ANSI/APA PRG-320: Standard for Performance-Rated Cross-Laminated Timber (ReThink Wood, 2018). CLT can also be used in building types III or V or in a performance-based alternative path to code compliance.

There is no prescriptive code path for the use of DLT under the current IBC. However, DLT can still meet code requirements through a performance-based alternative path for code compliance (Rethink Wood, 2018, p. 4)

NLT can be used in type IV (heavy timber) construction in the 2015 International Building Code. NLT can also be used in building types III or V or in a performance-based alternative path to code compliance (Binational Softwood Lumber Council, 2017, p. 23). NLT's use in type I or II buildings is relatively limited to roofs and non load-bearing walls (Binational Softwood Lumber Council, 2017, p. 25).

# CLT, DLT, & NLT Comparison

	CLT	DLT	NLT
<b>Advantages &amp; Differences</b>	<p>Multiple layers of material give CLT a bidirectional spanning capability that is structurally similar to a reinforced concrete slab (Karacabeyli &amp; Brad, 2013, p. 6).</p> <p>CLT has a bidirectional spanning capability for floors and roofs, whereas single-layer DLT and NLT can only structurally span in one direction (ReThink Wood, 2018, p. 2).</p> <p>In North America, compared to NLT and DLT, CLT currently has the most substantial body of research, testing, and code approvals.</p>	<p>Acoustic profiles can be CNC-milled into the panel face to absorb sound (StructureCraft, 2017, p. 4).</p> <p>There is no glue or curing time (except for minor finger-jointing glue), so panel production is faster than CLT (StructureCraft, 2017).</p> <p>By avoiding the use of glue, DLT also avoids the VOCs and environmental impacts from adhesive usage.</p> <p>At this time, DLT is generally less expensive to manufacture than CLT (StructureCraft, 2017).</p> <p>At this time, DLT only qualifies under the performance-path approach for code compliance.</p>	<p>Multiple sizes of dimensional lumber can be used in one panel to create a staggered or ribbed pattern, which can have acoustic benefits (ReThink Wood, 2018).</p> <p>NLT can be formed into compound curves, unlike CLT, which can only be curved in one direction (Binational Softwood Lumber Council, 2017).</p> <p>No specialized equipment is needed to fabricate, so the panels can be made on-site if necessary (ReThink Wood, 2018).</p> <p>Reclaimed or salvaged wood members can be used in NLT construction as it can alternate 2x6 and nonstructural (i.e. salvaged) 2x4 members (Hummel, 2018).</p> <p>Although NLT has similar code allowances as CLT, it cannot be used in exterior walls unless it is fire-treated or uses a performance-path approach (Binational Softwood Lumber Council, 2017, p. 23).</p>

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# CLT & Certification Programs

## Introduction

Using CLT in a project's design can help achieve environmental certifications in programs such as Passive House, LEED (Leadership in Energy and Environmental Design), and Living Building Challenge. CLT's thermal qualities can minimize operational energy needs, and the renewable, carbon-storing nature of CLT may reduce the embodied carbon of a project.



## About

USGBC's LEED (Leadership in Energy and Environmental Design) program is a building certification program based on achieving credits for improving a building's environmental performance (USGBC, 2013). CLT can contribute to the following credits from the current LEED version (V4):

### Building product disclosure and optimization - environmental product declarations:

*Requires at least 20 EPDs (conforming to ISO or EN standards) from at least five different manufacturers (USGBC, n.d.).*

- Select a CLT option with an EPD.

### Building life-cycle impact reduction: Whole-building life-cycle assessment:

*For new construction, conduct a cradle-to-grave life-cycle assessment of the project's structure and enclosure that demonstrates a minimum of 10% reduction, compared with a baseline building, in at least three of the six impact categories, one of which must be global warming potential. No impact category assessed as part of the life-cycle assessment may increase by more than 5% compared with the baseline metric (USGBC, 2013).*

- Buildings utilizing CLT for some or all of their structure consistently show lower impacts in whole building life cycle assessments (Grann, 2014; Robertson, Lam, & Cole, 2012; Teshnizi, Pilon, Storey, Lopez, & Froese, 2018).

## About

The Living Building Challenge is a sustainable design framework and green building certification program that certifies buildings based on verified (not just anticipated) performance in seven areas (Living Building Challenge, 2014). CLT can contribute to the following imperatives, which are necessary for certification:

### Imperative 09: Biophilic Environment:

*The project must include elements that nurture the innate human/nature connection.*

- Exposing the wood finish of CLT can contribute to this credit, as it is a natural element that allows for a human-nature interaction in the built environment.

### Imperative 11: Embodied Carbon

**Footprint:** *The project must offset total embodied carbon (tons of CO<sub>2</sub>e) impact from its construction through a one-time carbon offset from an approved carbon offset provider:*

- While there is not a consensus on the best way to account for carbon sequestered in CLT, some studies show that CLT has a lower embodied carbon than comparable structural materials. This would require less of a carbon offset for this imperative.

## About

The Passive House standard is a voluntary energy standard resulting in extremely energy efficient, comfortable, durable, and resilient buildings, while establishing readiness for a net zero or net positive energy path. The Passive House Institute U.S. (PHIUS) offers building standards that account for the broad range of climate conditions, market conditions, and other variables in North American climate zones. The German Passivhaus Institut (PHI) offers a quantifiable performance standard that is well-suited for the Central European and similar climate zones. Both standards seek to improve occupant comfort while simultaneously minimizing energy use. CLT can contribute to a Passive House design in the following ways:

### Thermal Insulation

- CLT's thermal mass, combined with its low conductivity, make it a good insulating material. (Waugh Thistleton Architects, 2018, p. 68).

### Thermal Bridging

- CLT and other wood materials have lower conductivity (transfer of energy) than steel and concrete across the building envelope. (Waugh Thistleton Architects, 2018, p. 68).

# CLT & Certification Programs



LIVING  
BUILDING  
CHALLENGE™



Passive House Institute US

## Building product disclosure and optimization - sourcing of raw materials:

*Requires at least 20 products with reports of raw material extraction information and efforts to reduce environmental harm OR 25% of products must meet responsible extraction requirements. For wood products, Forest Stewardship Council (FSC) certification is an accepted standard (USGBC, n.d.).*

- Use CLT with FSC-certified wood.

## Example LEED projects with CLT:

Wood Innovation and Design Centre  
Prince George, BC, Canada (2014)

The John W. Olver Design Building  
Amherst, MA, United State (2017)

Brock Commons Tallwood House  
Vancouver, BC, Canada (2017)

## Imperative 12: Responsible Industry

*Credit requirements: All materials must be sustainably sourced, and all wood must be FSC-certified.*

- Select a manufacturer that can produce FSC-certified CLT.

## Imperative 13: Living Economy

**Sourcing:** *A certain percentage of materials must be regionally sourced (20% of the material budget within 500 km, 30% of the material budget within 1000 km, and 25% of the material budget within 5000 km) (Living Building Challenge, 2014).*

- CLT manufacturers in the United States and Canada may fall within one of the required distances.

## Example Living Building Challenge projects with CLT:

Bullitt Center\*  
Seattle, WA, United State (2013)  
\*(uses NLT, a similar material to CLT)

## Airtightness

- The solid construction and fewer number of joints in CLT panel construction makes it easier to achieve airtightness than with post-and-beam constructions. The airtightness of CLT panels can further be increased through taping the inside of floor-to-wall joints, adding a compressed preformed gasket between wall and floor panels, and sealing the outside of the panel with barrier membranes if appropriate for climate and enclosure conditions (Exova BM Trada, 2017).

## Example Passive House projects with CLT:

Whistler Austria House  
Whistler, BC, Canada (2017)

Rocky Mountain Innovation Center  
Basalt, CO, United States (2015)

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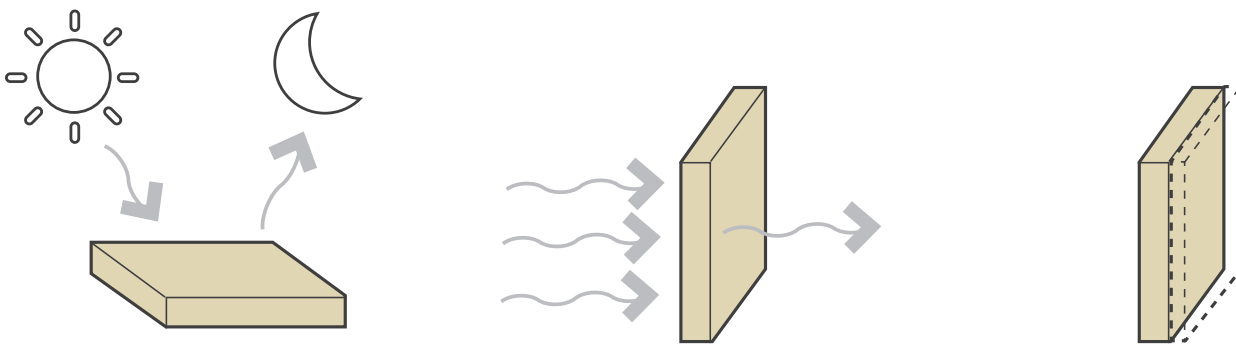
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# Net-Zero Design with CLT

## Introduction

In response to the building sector's impact on climate change, several organizations and governments are taking steps towards eliminating greenhouse gas emissions from building operational energy. A **net-zero building** requires that all operational energy be produced on-site on an annual basis. While net-zero is ideal, it is limiting and is not achievable in dense urban environments where tall buildings have high energy loads and limited roof area for on-site renewable energy generation. The 2030 Challenge, issued by Architecture 2030, and the AIA 2030 Commitment seek to make all new buildings and renovations **Zero-Net-Carbon (ZNC)** by 2030. A ZNC building produces on-site or procures off-site 100% of its energy demands through carbon-free renewable energy sources. Reducing the energy needs for a building's heating and cooling helps reduce the overall quantity of energy required. Using CLT in exterior wall or roof assemblies can help achieve ZNC or net-zero standards through reducing operational energy needs. CLT's thermal mass, low thermal bridging, and airtightness help create an energy-efficient envelope (Sutton, Black & Walker, 2011, p.2).



## 1 Dynamic Thermal Performance

CLT's thermal characteristics can contribute to a comfortable interior environment. A study located in Vienna, Austria, compares the ability of wall systems (with identical U-values) to maintain a comfortable indoor temperature. CLT wall types perform better than a light wood frame, as well as masonry block, but worse than the solid concrete wall (StoraEnso, n.d.). CLT's thermal properties seem best matched to mixed climates that have significant temperature swings, such as Sacramento and Atlanta (Karacabeyli & Brad, 2013, p. 420). Depending on the needs of a given climate, the thermal mass of CLT can be increased by adding additional thermal mass in the form of other materials, such as concrete. (Waugh Thistleton Architects, 2018).

## 2 Reduced Thermal Bridging

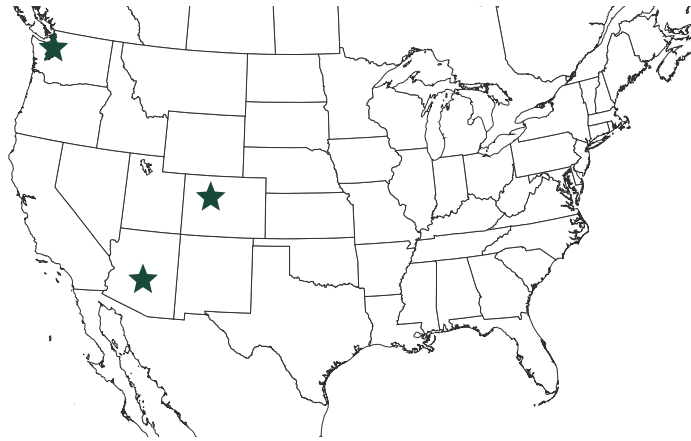
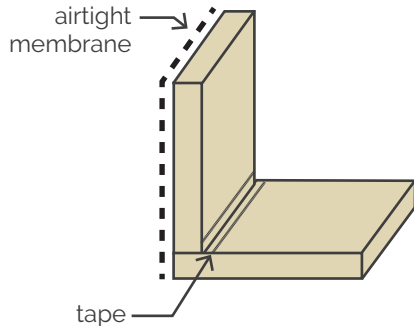
CLT has a lower thermal conductivity than steel or concrete, and it can help limit thermal bridging (transfer of energy) across the envelope. (Waugh Thistleton Architects, 2018, p. 68). The large size of the panel requires fewer connections (than steel frame construction) which could act as thermal bridges. CLT should be used in roofs and exterior walls to take advantage of this property. To further reduce thermal bridging, continuous insulation should be located on the exterior side of the CLT panels (Karacabeyli & Brad, 2013, p. 419). The vapor permeance of insulation and barrier membranes must be coordinated with climate and exterior cladding material for proper moisture management (Karacabeyli & Brad, 2013, p. 419).

## 3 Insulation Amount

In net-zero buildings, the thickness of insulation should be considered with the thermal mass to provide the optimum combination for thermal control. Wood is a good insulator, and CLT panels have an approximate R-value of 1.2 per inch thickness (Exova BM Trada, 2017). The insulation of CLT may be increased by using continuous, exterior-facing insulation of an additional breathable material such as wood fiber or mineral wool (Exova BM Trada, 2017). Exterior insulation is recommended for all climates to protect the CLT from temperature and moisture extremes that would lead to expansion, contraction, and moisture condensation on the panels (Karacabeyli & Brad, 2013, p. 419).



# Net-Zero Design with CLT



## 4 Airtightness

CLT panels help achieve airtightness due to their lack of gaps. The airtightness of CLT panels can be maximized through several methods. These methods include: taping the inside of floor-to-wall joints, adding a compressed preformed gasket between wall and floor CLT elements, and sealing the outside of the panel with barrier membranes if appropriate for climate and enclosure conditions (Exova BM Trada, 2017).

## 5 North American Net-Zero Examples

Rocky Mountain Institute's Innovation Center in Colorado was designed by ZGF Architects to be net-zero. The project features a CLT floor and roof, with glulam columns (Hill, 2015).

Although not a CLT building, the mass timber (NLT) design of the Bullitt Center in Seattle was intended to be net zero energy and water. (Mayo et al., 2014).

Future: Arizona State University's Interdisciplinary Science & 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 (Lubell, 2017).

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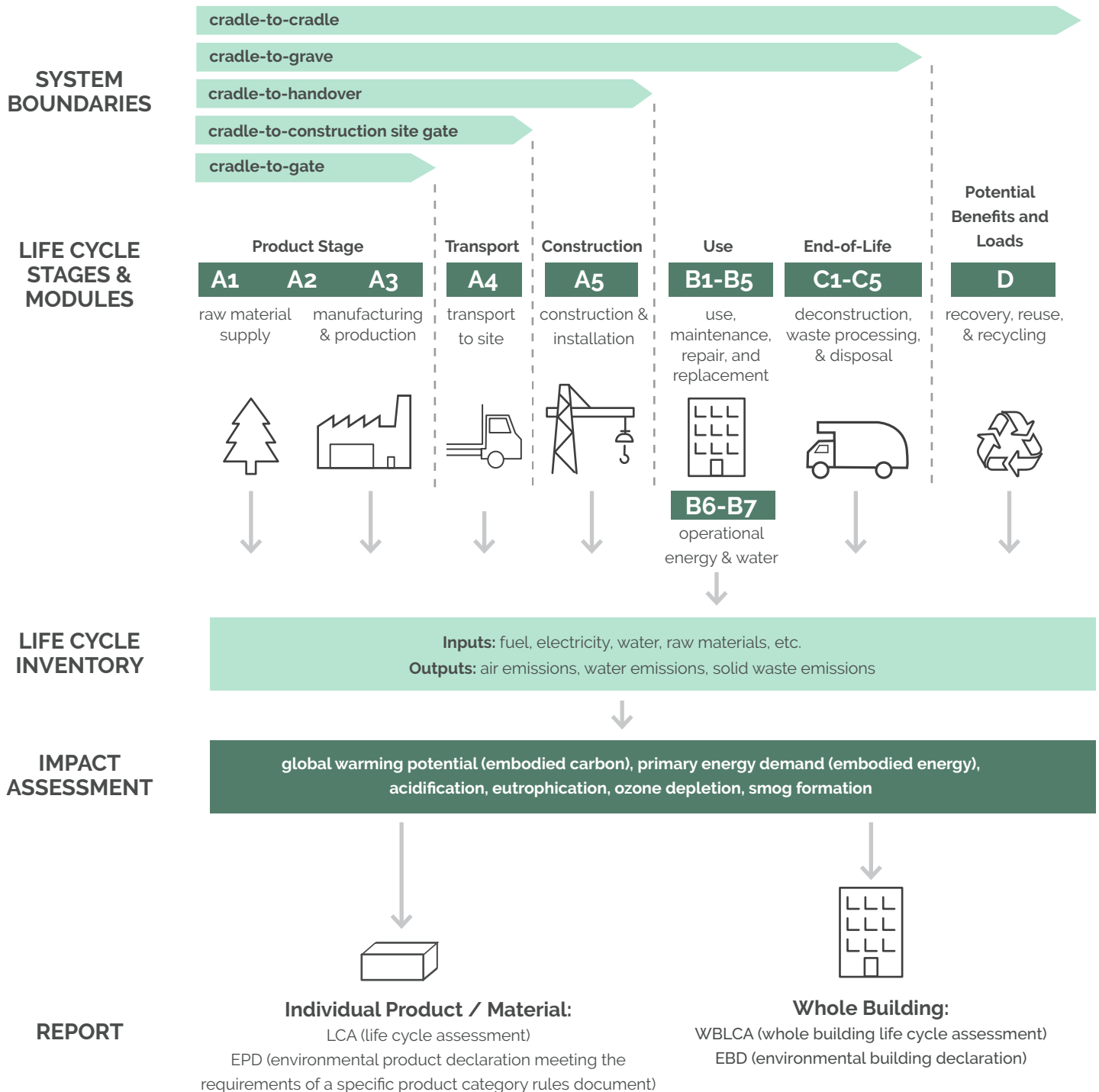
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# Intro to Life Cycle Assessment

## Introduction

Life cycle assessment (LCA) is a method for the collection and evaluation of the inputs, outputs, and the estimated environmental impacts of a product system in its life cycle. A suite of international ISO standards provide an overarching framework for this method, from which national and third party programs derive more specialized guidelines. A life cycle assessment can be carried out at the scale of a single product or a whole building and generally will have a goal of reducing or communicating environmental impacts. A diagram of the components of a life cycle assessment is shown below.



# Intro to Life Cycle Assessment

## **CO<sub>2</sub> eq (carbon dioxide equivalent)**

The cumulative quantity of CO<sub>2</sub> and other greenhouse gases (such as methane, or nitrous oxide). The quantities of other greenhouse gases are converted into the equivalent quantity of CO<sub>2</sub> that would create the same amount of global warming as the greenhouse gas

## **Embodied Carbon**

(Also known as embodied greenhouse gases) the sum of greenhouse gases (regardless of their type) emitted in one or more life cycle stages of a product (typically does not include operational energy), typically expressed as the global warming potential and measured in **kg CO<sub>2</sub> eq.**

## **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/m<sup>2</sup>**

## **Environmental Impacts**

Impact categories typically included in an **LCA** include: global warming potential, acidification, eutrophication, ozone depletion potential, and smog formation potential

## **Environmental Product Declaration**

a standardized way of quantifying and communicating the environmental impact of a product or system

## **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<sub>2</sub> eq.**

## **LCA (Life Cycle Assessment, Life Cycle Analysis)**

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. Frequently used tools include Gabi, SimaPro, and Open LCA.

## **Product Category Rules**

A third party document that establishes specific rules, requirements, and guidelines for developing an **EPD** for one or more product categories

## **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.

## **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. Frequently used tools include Athena, Tally, One Click LCA, and LEGEP

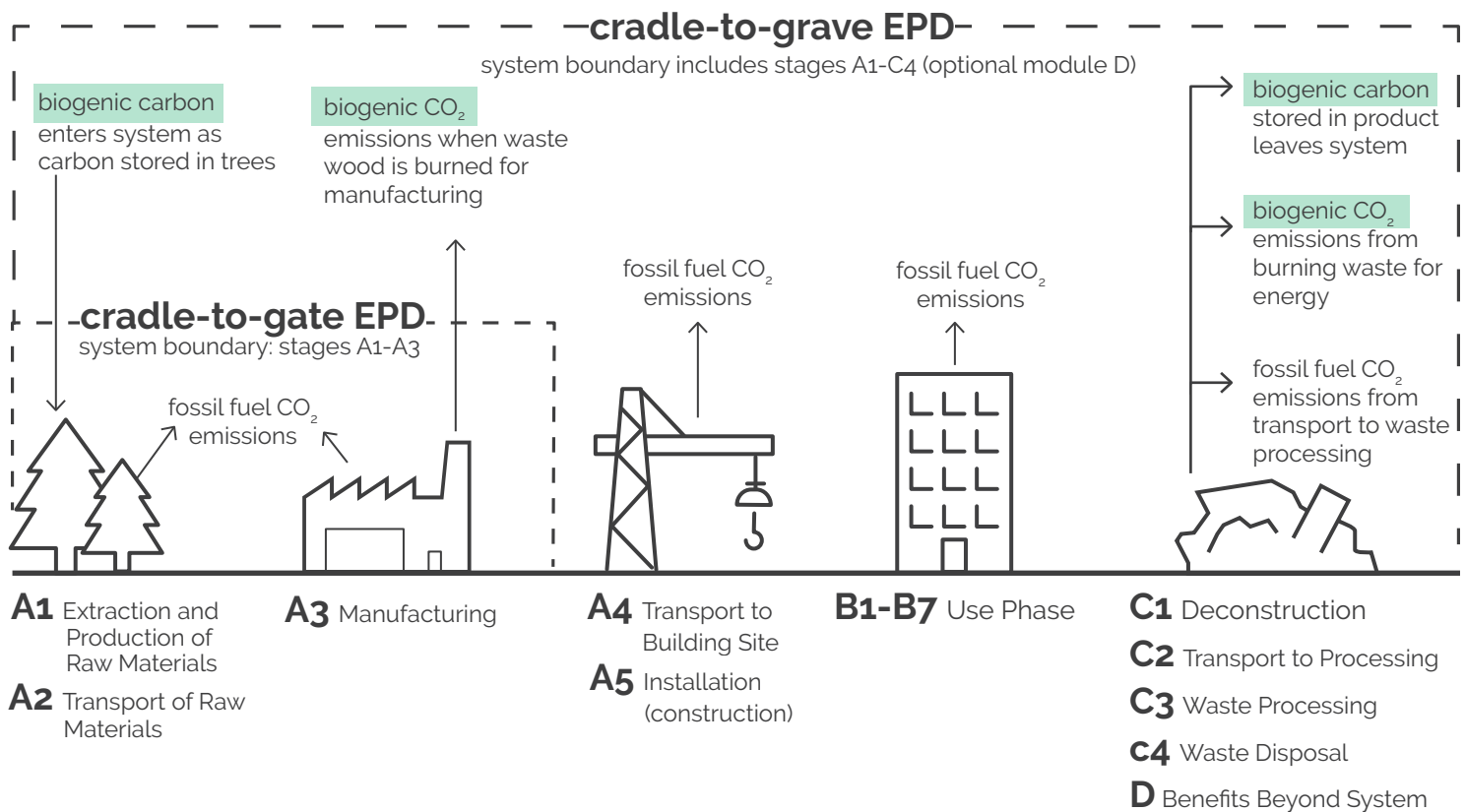


# CLT EPDs & Biogenic Carbon

## Introduction

Manufacturers report greenhouse gas (including CO<sub>2</sub>) emissions from the manufacturing of CLT in an environmental product declaration (EPD), under the category of global warming potential (GWP). Product category rules (PCR) determine the methodologies that an EPD must follow, and the emissions are divided according to defined life cycle stages of A, B, C, and D. EPDs can report impacts from all life cycle stages or only a selection. A "cradle-to-gate" EPD includes the life cycle stages from forest (the "cradle") to the completion of the product at the factory "gate."

For wood products, the treatment of **biogenic carbon** affects the quantity of CO<sub>2</sub>eq emissions associated with the product. **Biogenic carbon** is "carbon derived from/contained in biomass," and **biomass** is "material of biological origin excluding material embedded in geological formations and material transformed to fossilized material" (CEN, 2014, p. 7). Biogenic carbon makes up approximately 50% of tree tissue. Biogenic carbon also is used to refer to the CO<sub>2</sub> emitted into the atmosphere when biomass is burned for energy. The diagram below shows the biogenic carbon flows and life cycle stages for wood products in a North American EPD.



Guidelines from the 2015 FPIInnovations PCR for North American Structural and Architectural Wood Products:

## biogenic carbon in cradle-to-gate EPD

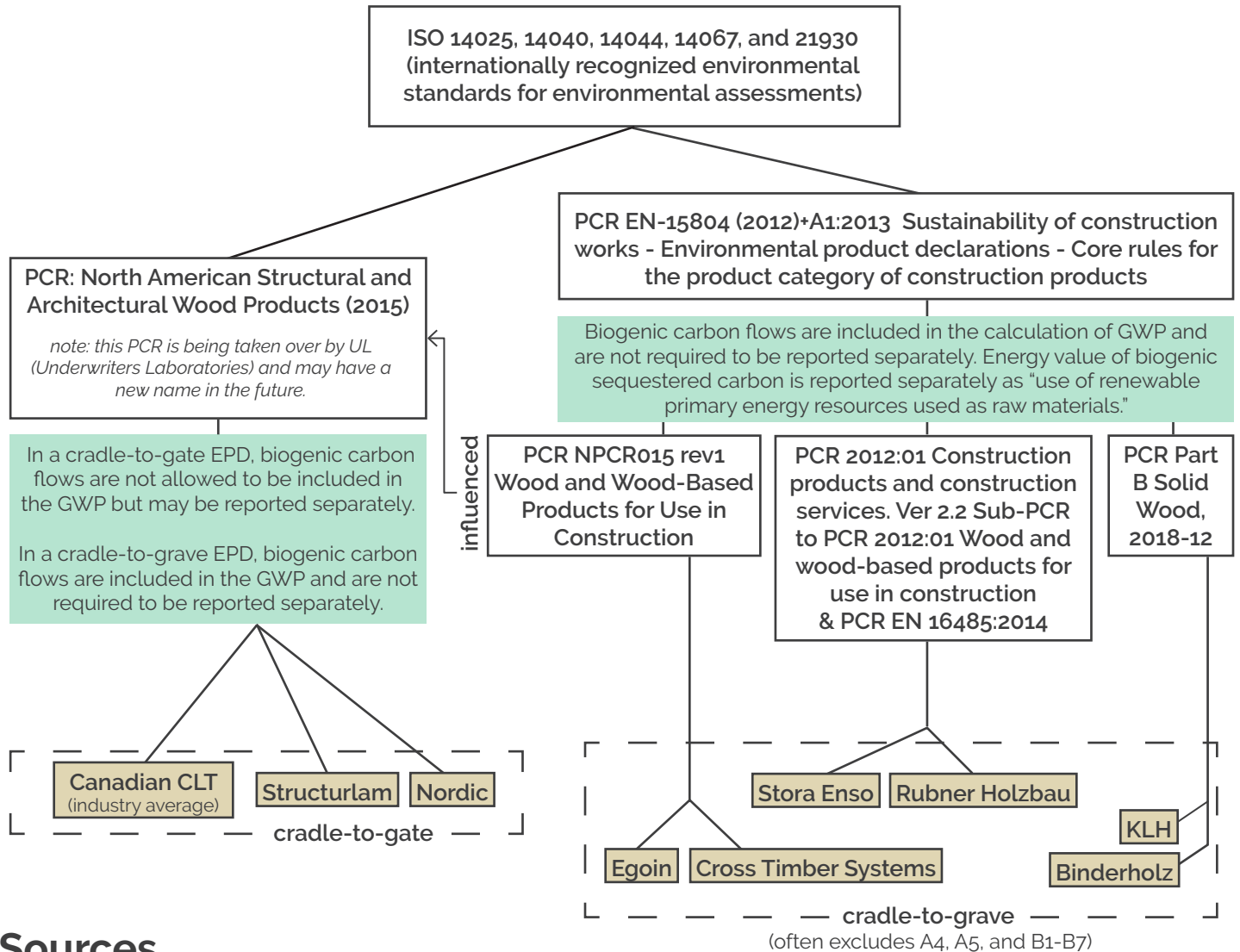
- The 2015 FPIInnovations PCR **does not** allow biogenic stored carbon (or biogenic carbon emissions) to be added to the GWP for a cradle-to-gate EPD (whereas EN15804 / EN16485 does). Under this PCR, biogenic carbon information may be noted in module "D."
- For a sustainably-managed source, it is assumed that biogenic CO<sub>2</sub> emissions do not contribute to GWP when the whole product life cycle is considered (FPIInnovations, 2015).

## biogenic carbon in cradle-to-grave EPD

- The 2015 FPIInnovations PCR **allows** biogenic carbon (storage and emissions) to be added to the GWP as carbon enters and leaves the system within each stage.
- For a sustainably-managed source, it is assumed that biogenic CO<sub>2</sub> emissions do not contribute to GWP when the whole product life cycle is considered (FPIInnovations, 2015), (CEN, 2014). Therefore, the biogenic carbon sequestration is assumed to be equal to the biogenic carbon emissions.

# CLT EPDs & Biogenic Carbon

## Legend



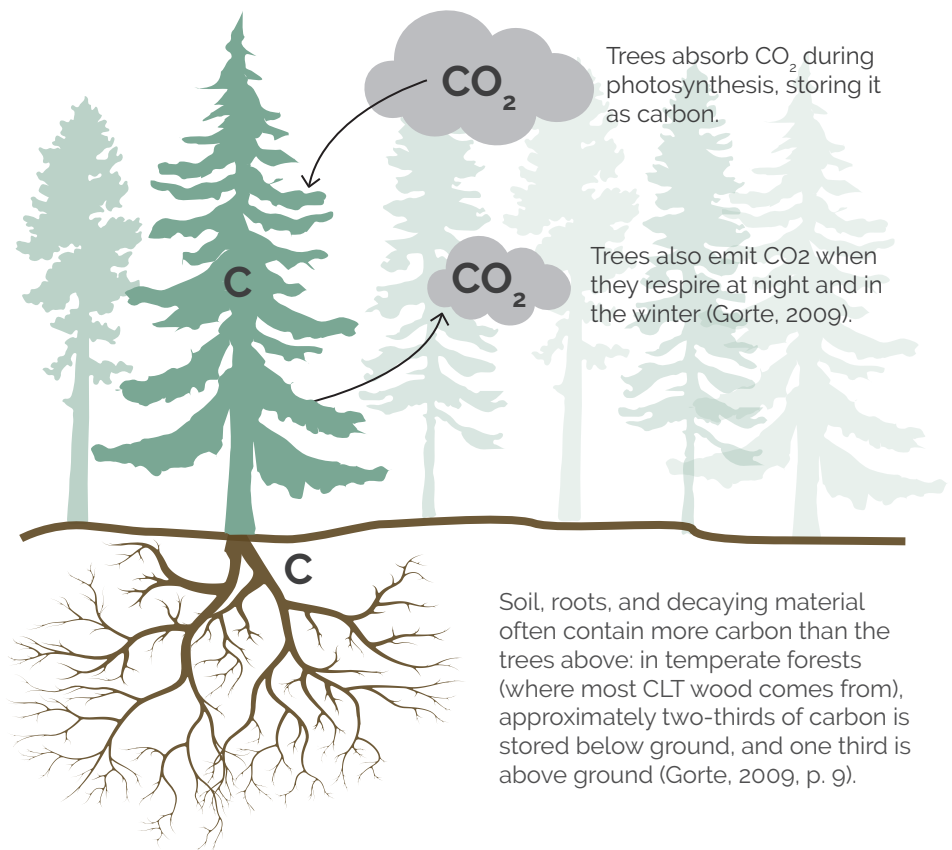
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- Refer to manufacturers' websites for current EPD documents

# Carbon Content of CLT

## Introduction

Approximating the stored (sequestered) CO<sub>2</sub> within CLT allows for a better understanding of potential environmental benefits of CLT. The carbon content of CLT should always be considered in the context of the whole life carbon emissions from manufacturing, use, and disposal (end of life). Carbon content is typically expressed as the equivalent quantity of carbon dioxide, the greenhouse gas that contributes to global warming. The exact quantity of CO<sub>2</sub> that CLT stores varies based on wood species and the density of a specific manufacturer's CLT panel composition. Carbon content and densities should be based on values of oven-dry wood, in order to exclude moisture content from weight and density. The widely-used value of 50% for wood's carbon content is not as accurate as species-specific averages (Jones & O'Hara, 2018).



## approximating the carbon content of 1 m<sup>3</sup> of CLT

$$\frac{406 \text{ kg wood}}{\text{m}^3 \text{ of CLT}} \times \frac{0.498 \text{ kg C}}{\text{kg wood}} \times \frac{44 \text{ atomic mass units}}{12 \text{ atomic mass units}} = 741 \text{ kg CO}_2$$

### oven-dry density of a CLT panel

The density of the wood depends on the manufacturer and the species used (often multiple species are used in one CLT panel)

### wood carbon content (%)

The oven-dry wood carbon content varies by species of wood. EN16449, a technical standard for wood carbon calculation, requires the use of a 50% average value (.5 kg carbon per kg wood). However, the actual carbon content of specific species is sometimes more and sometimes less than 50% (Jones & O'Hara, 2018).

### molecular weight ratio

The weight of carbon is 12 atomic mass units, but the weight of carbon dioxide is 44, (the two oxygen atoms each weigh 16 atomic mass units) (WoodWorks Wood Products Council, n.d, p. 3.).

### carbon dioxide content of CLT

This quantity does not including impacts from transportation to construction site, construction, and disposal at end-of-life. **When additional emissions from all life stages are considered, CLT may result in more carbon dioxide emitted than it stored (based on environmental product declaration data from CLT manufacturers).** Also, this number does not reflect environmental impacts of specific forestry practices on the carbon storage of the forest stand as a whole.



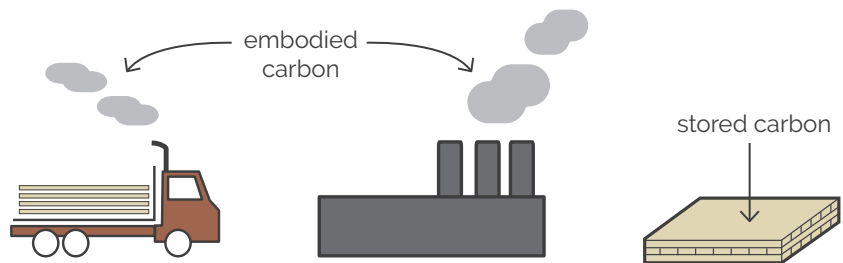
# Carbon Content of CLT

## FAQ



### Is wood 50% carbon?

Carbon content varies between tree species, within a tree species, and within a tree. Carbon content between tree species can vary between 46-59%, and conifers typically have a higher carbon content (Lamlom & Savidge, 2013, p. 382). A 50% carbon content estimate is inadequate; using species-specific averages would improve carbon content estimates (Jones & O'Hara, 2018). There is no international standard source for the carbon content of different tree species, so the value of 50% is usually used in the standard method for calculating biogenic carbon in tree tissues. Using an average value of 50% for all species potentially reduces the accuracy of stored carbon calculations.



### What is the difference between embodied and stored carbon?

**Embodied carbon** (commonly referred to as embodied greenhouse gases or carbon footprint) refers to the sum of greenhouse gas emissions associated with a building or material. The quantity can be subdivided into initial (manufacturing and construction) emissions, recurring emissions (from maintenance and replacement), and demolition emissions (Melton, 2018, p. 2).

**Stored/sequestered carbon** refers to the carbon dioxide that has been transformed into carbon and contained within a material. Wood stores carbon dioxide (as carbon) through photosynthesis and concrete stores minor amounts of carbon dioxide (as carbon) through the carbonation of cement over its useful lifetime, although this can be increased at the end of life. However, for wood, some of this stored carbon can be re-released into the atmosphere during decomposition after demolition through waste treatment processes (refer to info sheet #14).

### How can I estimate the amount of stored carbon in wood products in a building?

For a rough estimate of stored carbon, WoodWorks Wood Products Council provides a calculator to estimate the amount of carbon sequestered in a building that utilizes wood products. The calculator assumes that all wood has a carbon content of 50% (WoodWorks Wood Products Council, n.d.).

To understand the stored carbon within the context of carbon dioxide emissions, a whole building life cycle assessment should be conducted.

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# CLT Life Cycle Analysis (cradle-to-gate)

## Introduction

A cradle-to-gate life cycle assessment for CLT measures the inputs and outputs (and characterizes their environmental impacts) starting with the resource extraction (lumber production) at the forest, and ending with the finished CLT panel at the factory gate (refer to info sheet #9). Inputs, outputs, and their corresponding environmental impacts are measured in their quantities per 1 m<sup>3</sup> finished CLT product. Per ISO 14067 and ISO 21930 guidelines, as well as the North American PCR for Structural and Architectural Wood Products, the biogenic carbon dioxide emissions from wood waste are not included in the calculation of global warming potential, but the methane and NO<sub>x</sub> emissions from that process are included (FPLInnovations, 2015).

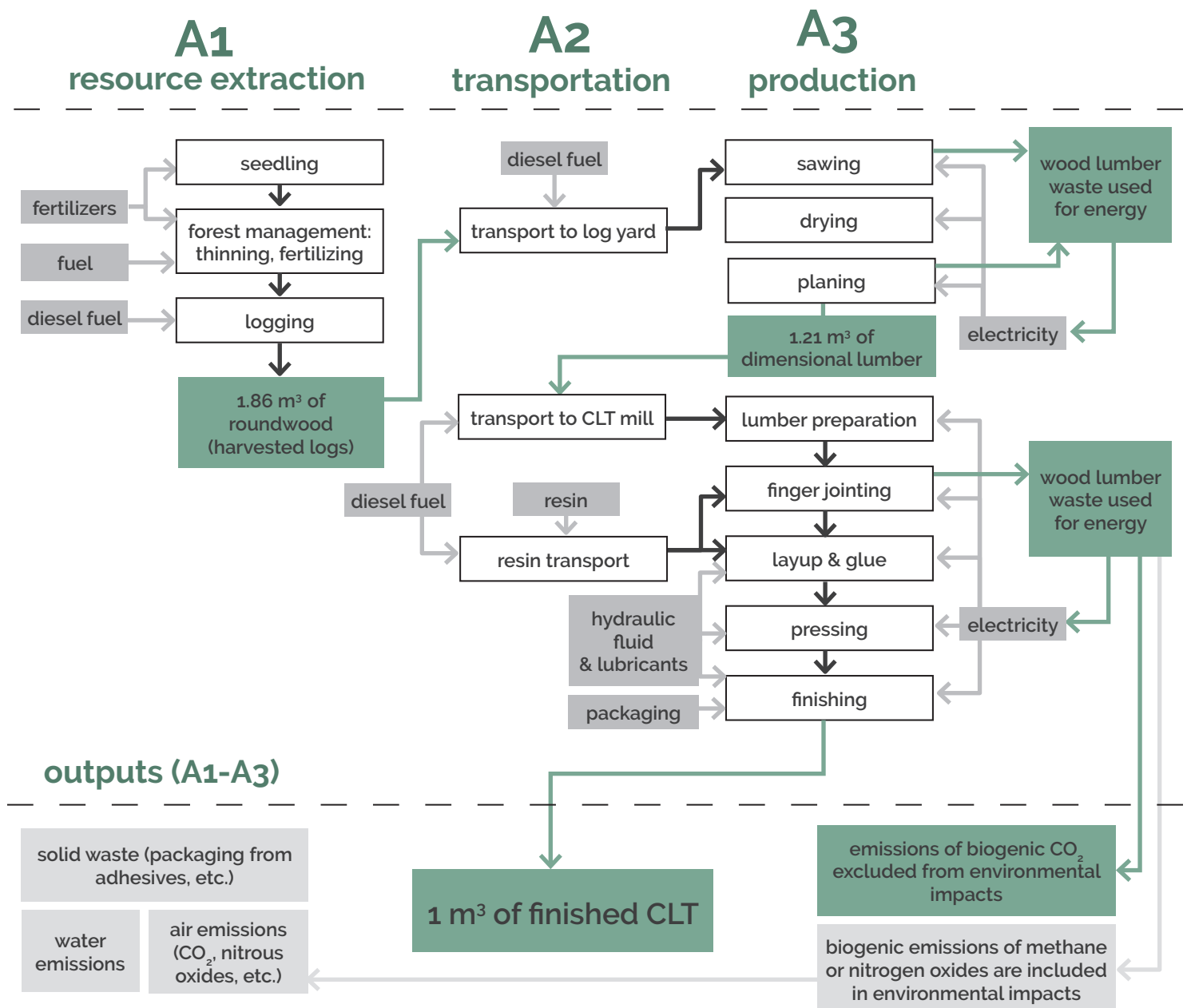
## Legend

typical inputs

system process

typical outputs

biogenic flows



# CLT Life Cycle Analysis (cradle-to-gate)

## Environmental Impacts per 1 m<sup>3</sup> of North American CLT

*\*note that EPDs below should not be directly compared due to possible differences in scope or calculation methods*

	Manufacturer 1	Manufacturer 2	Manufacturer 3
<b>Global Warming Potential</b>	<b>121.89</b> kg CO <sub>2</sub> eq	<b>206.26</b> kg CO <sub>2</sub> eq	<b>89.80</b> kg CO <sub>2</sub> eq
<b>Acidification</b>	<b>1.19</b> kg SO <sub>2</sub> eq	<b>2.27</b> kg SO <sub>2</sub> eq	<b>44.24</b> H <sup>+</sup> moles eq
<b>Eutrophication</b>	<b>0.11</b> kg N eq	<b>0.11</b> kg N eq	<b>0.11</b> kg N eq
<b>Ozone Depletion Potential</b>	<b>1.79E-06</b> kg CFC-11 eq	<b>0</b> kg CFC-11 eq	<b>2.15E-07</b> kg CFC-11 eq
<b>Smog Formation</b>	<b>35.53</b> kg O <sub>3</sub> eq	<b>41.98</b> kg O <sub>3</sub> eq	<b>17.46</b> kg NO <sub>x</sub> eq
<b>Cumulative Energy Demand</b>	<b>2,786.74</b> MJ	<b>5,839.96</b> MJ	<b>1,472.26</b> MJ

(FPInnovations, 2018)

(Puettmann et al., 2018)

(FPInnovations, 2013b)

### Global Warming Potential

Global warming potential is the cumulative contribution to potential global warming from carbon dioxide and greenhouse gas emissions. GWP is expressed in terms of kg CO<sub>2</sub> eq. (Bare, 2012, p. 18).

### Acidification

The increasing concentration of H<sup>+</sup> (hydrogen ions) in an environment causes damage in human and natural environments. Acidification can cause acid rain, corroding buildings and other structures (Bare, 2012). Nitrogen oxides (NO<sub>x</sub>) and sulfur dioxide (SO<sub>2</sub>) emitted from fossil fuel production cause acidification. In North America, acidification is typically reported in kg SO<sub>2</sub> eq. (Bare, 2012, p. 18).

### 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). An LCA of CLT produced in Oregon reports that resin contributes 57% of the cradle-to-gate eutrophication impact (Puettmann, Sinha, & Ganguly, 2018).

### Ozone Depletion Potential

Communicates the potential impact of substances that deplete the protective stratospheric ozone layer. Various chlorofluorocarbons are expressed as kg CFC-11 equivalents (Bare, 2012, p. 18).

### Smog Formation

Smog is created through the reactions of nitrogen oxides (NO<sub>x</sub>) and volatile organic compounds (VOCs) in the atmosphere. In North America, smog formation is typically quantified in kg O<sub>3</sub> eq (Bare, 2012, p. 18).

### Cumulative Energy Demand

Cumulative energy demand is the sum of all energy (renewable and non-renewable) used in the product's life cycle. Cumulative energy demand is expressed in MJ and also known as embodied energy.

## Environmental Impacts NOT Accounted for in EPDs/LCAs

EPDs and LCAs do not account the effects of forest management practices and their impact on carbon stored in the forest, or on biodiversity. They also do not account for environmental impacts beyond the system boundary, such as employee transportation.

## Sources

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# CLT Production Carbon Impacts

## Introduction

Several North American CLT manufacturers provide environmental product declarations (EPDs) or life cycle assessments (LCAs) that communicate the greenhouse gas emissions associated with their CLT's production. For North American CLT, the current standard for EPDs is FPIInnovations' PCR for North American Structural and Architectural Wood Products (2015). This PCR specifies the inclusion of ancillary materials (such as hydraulic fluids, lubricants and packaging), and the exclusion of human activity (such as personal transportation to the factory and capital equipment). The environmental impacts are reported separately by product life cycle stages (refer to info sheet #12 for a diagram of CLT production stages).

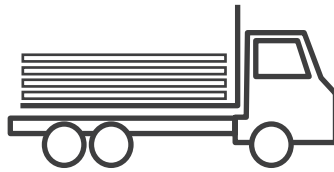
Below, example CO<sub>2</sub>eq emissions from CLT manufacturing are shown for each product manufacturing stage (A1-A3). This information comes from three EPDs of two different Canadian CLT manufacturers, from three different production years. Each EPD uses a different version of the FPIInnovations' PCR, so the results cannot be directly compared (but nevertheless indicate an general range of relative impacts). Nordic is the CLT manufacturer of **EPD 1**, located in Chibougamau, Quebec (Canada). EPD 1 calculates Nordic's CO<sub>2</sub> emissions based on the guidelines of FPIInnovations' PCR (2015 version), while **EPD 2** (2013) shows Nordic's CO<sub>2</sub> emissions based on the 2011 version of FPIInnovations' PCR. **EPD 3** shows the emissions from Strucurlam, a CLT manufacturer based in Penticton, British Columbia (Canada). EPD 3 is based on the 2013 version of FPIInnovations' PCR.

## Example CLT Manufacturing CO<sub>2</sub>eq Impacts for 1 m<sup>3</sup> of CLT (Canadian Manufacturers)



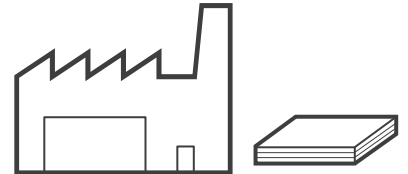
### A1 Logging, Nursery, Site Preparation, Planting, & Forest Management

Includes energy for harvesting (diesel, gasoline etc.) and ancillary materials (e.g., lubricants, motor oil, grease).



### A2 Transportation to Manufacturing Facility

Transportation via truck consumes diesel fuel, emitting CO<sub>2</sub>. Distance of harvesting site to factory determines the magnitude of impacts. Transportation includes secondary materials, such as adhesives.



### A3 Sawmilling, Drying, Adhesive and Packaging, Pressing CLT Panels

18% (EPD 2) to 39% (EPD 3) of energy for CLT manufacturing comes from waste wood, and these biogenic emissions are excluded from the GWP, per the PCR (FPIInnovations, 2013a; FPIInnovations, 2013b).

#### Impacts per 1 m<sup>3</sup> of CLT

EPD 1 (2018) GWP: **37.88** kgCO<sub>2</sub>eq

EPD 2 (2013) GWP: **12.00** kgCO<sub>2</sub>eq

EPD 3 (2013) GWP: **11.38** kgCO<sub>2</sub>eq

#### Impacts per 1 m<sup>3</sup> of CLT

EPD 1 (2018) GWP: **51.97** kgCO<sub>2</sub>eq

EPD 2 (2013) GWP: **28.59** kgCO<sub>2</sub>eq

EPD 3 (2013) GWP: **27.12** kgCO<sub>2</sub>eq

#### Impacts per 1 m<sup>3</sup> of CLT

EPD 1 (2018) GWP: **32.04** kgCO<sub>2</sub>eq

EPD 2 (2013) GWP: **29.93** kgCO<sub>2</sub>eq

EPD 3 (2013) GWP: **51.29** kgCO<sub>2</sub>eq

# CLT Production Carbon Impacts

## Canadian CLT Manufacturing Impacts: Total Sum for Categories A1-A3

EPD 1 (2018) GWP: **121.89** kgCO<sub>2</sub>eq

EPD 2 (2013) GWP: **70.52** kgCO<sub>2</sub>eq

EPD 3 (2013) GWP: **89.90** kgCO<sub>2</sub>eq

## For comparison: estimated stored carbon (dioxide) in 1 m<sup>3</sup> of CLT

EPD 1 (2018) Stored Carbon: **741.36** kgCO<sub>2</sub>eq

EPD 2 (2013) Stored Carbon: **764.56** kgCO<sub>2</sub>eq

EPD 3 (2013) Stored Carbon: **764.56** kgCO<sub>2</sub>eq

## Discussion

The above estimates of CO<sub>2</sub>eq emissions indicate ranges from different locations, different years of data and PCR versions. All examples are based on FPInnovations' Product Category Rules, but EPD 1, 2, and 3 are based on the 2015, 2011, and 2013 versions, respectively. Some differences between values could be due to adhesive types. Nordic (EPD 1 and 2) uses polyurethane and isocyanate, while Structurlam uses polyurethane and arclin melamine) and inclusion/exclusion of packaging (Nordic includes; Structurlam excludes). Other likely causes include: varying carbon intensities of electricity grid energy sources, different tree species, and minor adjustments with consecutive PCR versions.

## Biogenic Carbon

FPInnovations' product category rules specifies that the biogenic carbon impacts can only be included if the EPD covers the whole life cycle from harvest to product end-of-life. The Canadian CLT manufacturers only include harvest through manufacturing, so they must exclude this information from the GWP. The practice of excluding biogenic carbon emissions from biomass products is common practice in life cycle assessments and carbon stock accounting. Biogenic carbon emissions are counted as "carbon neutral" because when forests are managed sustainably, forest regeneration will reabsorb the carbon dioxide harvest emissions. However, where forests are not managed sustainably, or where there is land use change, the carbon storage of regrowth will not meet prior levels. The shortcomings of the biogenic carbon neutrality assumption have been widely discussed (Searchinger et al. 2009); 'carbon neutral' does not automatically mean 'climate neutral' (Cherubini et al. 2011). Due to the timing of harvest and production emissions, biogenic carbon flows in wood products can have a net climate change effect, because new trees cannot reabsorb the carbon dioxide as fast as it is emitted.

## Sources

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### EPD 2 Nordic CLT / FPInnovations 2011

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### EPD 3 Structurlam CLT / FPInnovations 2013

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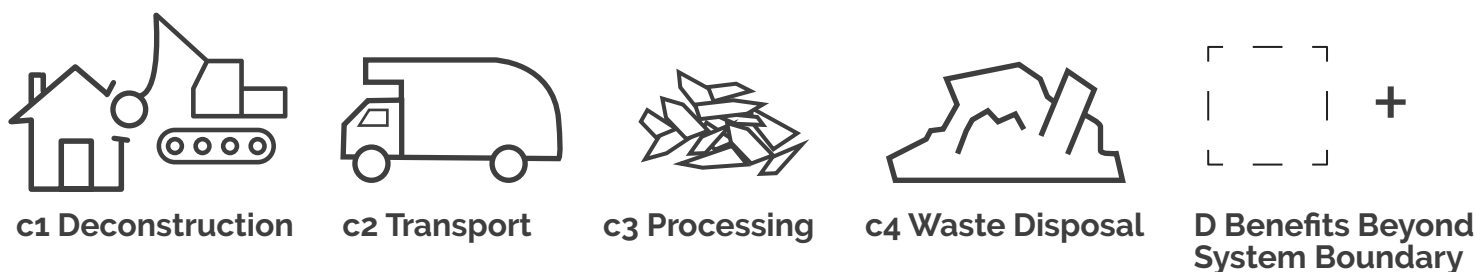
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# End-of-Life CLT Carbon Impacts

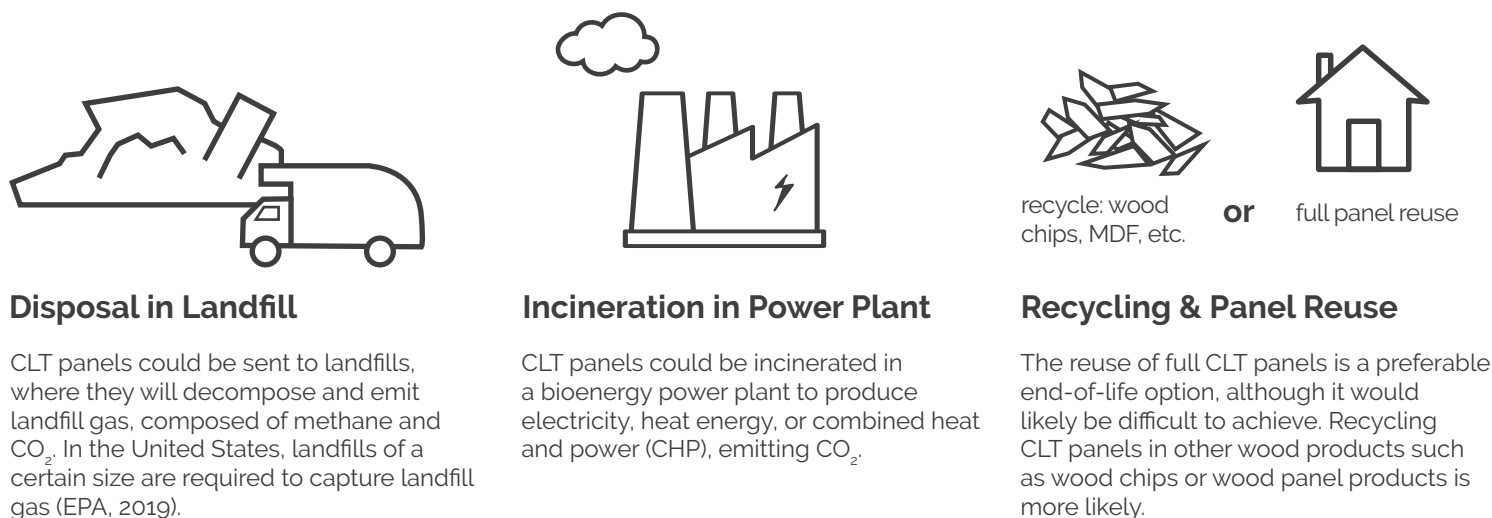
## Introduction

At the end of CLT's usable life, when a building is demolished or dismantled, the end-of-life scenario and assumptions have a significant impact on greenhouse gas (calculated as CO<sub>2</sub>eq) emissions. The primary scenarios for end-of-life are **landfill**, **incineration** (to produce power), and **recycling** (either reuse of panels or recycling the wood in a different product). In a study comparing environmental impacts of end-of-life for wood products, Morris analyzes landfill, incineration, and recycling using three different sets of assumptions and methods (2016). Incineration was typically the least preferable option when assessing the combined climate, human health, and ecosystems perspective, especially when substituting for natural gas (Morris, 2016). Estimating the end-of-life fate of any material in the future contains uncertainties about future efficiencies of waste facilities, as well as regulation on construction waste disposal practices.

A cradle-to-grave LCA or EPD shows a product's end-of-life environmental impacts in module C (further divided into C1 - Deconstruction, C2 - Transport, C-3 Waste Processing, C-4 Disposal) and module D (refer to info sheet #10). Module D shows impacts beyond a system boundary. It is a cut-off approach to avoid double-counting of carbon; the entity sending a product to be recycled and the entity receiving the recycled product cannot both claim the environmental benefit.



## End-of-Life Scenarios for CLT panels



### Disposal in Landfill

CLT panels could be sent to landfills, where they will decompose and emit landfill gas, composed of methane and CO<sub>2</sub>. In the United States, landfills of a certain size are required to capture landfill gas (EPA, 2019).

### Incineration in Power Plant

CLT panels could be incinerated in a bioenergy power plant to produce electricity, heat energy, or combined heat and power (CHP), emitting CO<sub>2</sub>.

### Recycling & Panel Reuse

The reuse of full CLT panels is a preferable end-of-life option, although it would likely be difficult to achieve. Recycling CLT panels in other wood products such as wood chips or wood panel products is more likely.

- + some carbon stored indefinitely; landfill gas can be used to produce energy
- landfill gas contains methane, which has greater global warming potential than an equivalent quantity of CO<sub>2</sub>

- + power produced from bioenergy (burning wood like CLT) potentially avoids fossil fuel use.
- carbon from CLT is released as CO<sub>2</sub>, and the bioenergy power plant might not result in actual reduction in fossil fuel use

- + reprocessing of material potentially avoids the growth and harvest of virgin wood
- recycling the material may not actually lead to a reduction in the harvest of virgin wood

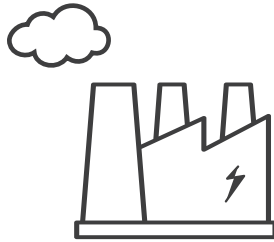


# End-of-Life CLT Carbon Impacts



## Disposal in Landfill

Wood decays in landfills through aerobic and anaerobic processes. For wood disposed of in the United States, WARM (Waste Reduction Model) is typically used to model end-of-life emissions for use in LCAs and EPDs. WARM assumes that approximately 12% of carbon in dimensional lumber will be emitted, with the remaining 88% being stored (US EPA, 2016, p. 116). Decaying wood produces landfill gas, composed of approximately 50% CO<sub>2</sub> and 50% methane, which has a 28 to 36 times higher global warming potential than CO<sub>2</sub> (US EPA, 2019). Landfill gas emissions depend on moisture, temperature, landfill gas management procedures, other waste products in the landfill (Moncaster & Symons, 2013, p. 3), and wood species (Wang et al. 2012). Approximately 72% of landfills that capture gas in the United States use the gas to produce energy (US EPA, 2019). Landfill impacts reported in module D would be avoided fossil fuel use if landfill gas is burned for energy.



## Incineration in Power Plant

Incineration in a biomass power plant avoids fossil fuel consumption (the benefit of which could be reported in module D). However, burning wood for fuel still results in CO<sub>2</sub> emissions. The potential benefit largely depends on the comparative electricity mix (whether it is natural gas, coal, or other) as well as the assumed efficiency of the biomass power plant. The greatest benefit of sending wood to a biomass power plant will occur when the plant has a high efficiency and avoids coal use (Morris, 2016).



recycle: wood chips, MDF, etc.

or



full panel reuse

## Recycling & Panel Reuse

Full panel reuse is an ideal scenario, which has already occurred in Japan (Passarelli, 2018). They found that reusing the panels resulted in a lower GWP than incinerating for landfill recovery. However, reuse of the panels resulted in 30% waste material and the energy to reconfigure the panels (Passarelli, 2018).

If CLT panels are recycled for the creation of wood chips or MDF panels, there will be emissions associated with transport and processing the panels into wood chips. Benefits beyond the system boundary, module D, would report the avoided harvest of virgin wood for these products. Assuming an avoided harvest of wood, Morris found that recycling wood products is generally the environmentally preferable scenario over landfilling and incineration (2016).

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# Embodied Carbon of CLT buildings

## Introduction

**Embodied carbon** (also referred to as embodied greenhouse gases or carbon footprint) is the total amount of greenhouse gas emissions associated a material or the materials that make up a building. However, there is no standard for what life cycle stages of a building or material must be included in this definition. Some define it as all carbon emissions prior to building operation, while others include the use phase of the building (repair, maintenance, replacement, etc.) and end-of-life impacts (landfilling, recycling, etc.) (Melton, 2018, p. 2). It can be subdivided into initial, recurring, and demolition embodied carbon. Commonly, it refers to the greenhouse gases emitted from a material's **manufacturing, transportation and construction**. However, a holistic understanding of a material's carbon impact should include use and end-of-life phases as well.

Some whole building life cycle assessment (**WBCLA**) studies suggest that buildings using CLT for some or all of the structure have lower **embodied carbon** than comparable steel or concrete structures (Gu & Bergman, 2018; Hafner & Scafer, 2018; Robertson, Lam, & Cole, 2012; Teshnizi, Pilon, Storey, Lopez, & Froese, 2018). Whole building life cycle assessment (**WBCLA**) is the process of evaluating the environmental impacts from the life cycle of a building, including material production, construction, building use (maintenance and any anticipated material replacements), and end-of-life activities (Athena, 2017). Embodied carbon is expressed in the WBCLA category of global warming potential (**GWP**). Software tools for WBCLA include but are not limited to, Athena Impact Estimator for Buildings, Tally, and OneClickLCA. WBLCAs can help inform building design decisions, but they are limited by their assumptions and uncertainties about the future of materials.

WBCLA studies usually do not take into account CLT connections, sealants, tapes, or additional fireproofing measures that may be required. Additionally, they may use life cycle information from glulam or lumber as a proxy for CLT.

## Case Studies



### 1-4 story residential WBCLA

Hafner and Schafer performed a WBCLA on several housing types, with the German software LEGEP. Using CLT for the primary building elements could lower GWP from 35% up to 56% in one story residential buildings when compared to various traditional structures of concrete and brick in a cradle-to-grave comparison. Using CLT could lower GWP between 9 and 48% in multistory buildings. These studies do not include a negative credit for carbon storage in the final result, assuming that the stored carbon is returned to the atmosphere at the end-of-life. The lower GWP reduction in the multistory buildings is attributed to the additional materials needed for fire protection (2018, p. 639).



### 4 story educational WBCLA

A mass timber building (CLT floors and roof, with glulam columns/beams) was compared to a hypothetical concrete and steel building, achieving at least a 10% reduction in all tracked environmental impact categories in a cradle-to-grave life cycle assessment. Notably, the mass timber building has a 13.1% lower GWP than the concrete building. This study, using the software Athena, includes the carbon storage of wood as a credit (negative) contribution to GWP (Gu & Bergman, 2018). The study also includes the carbon storage of concrete through the process of carbonation.



### 18 story educational WBCLA

A cradle-to-grave WBCLA comparison of an eighteen story mass timber (CLT and glulam) building with a comparable eighteen story concrete building at the University of British Columbia reveals that the CLT building has approximately 9% lower environmental impacts in five of six environmental impact categories. The CLT building has a 25% lower GWP than the concrete building (Teshnizi, Pilon, Storey, Lopez, & Froese, 2018, p. 174-175). This study includes the carbon storage of wood as a credit (negative) contribution to GWP and was done with Athena.

# Embodied Carbon of CLT buildings



## 5 story office building WBLCA (location: Canada)

A structure and enclosure comparison finds that a CLT hybrid system (glulam structure, CLT floors, and concrete cores) has a lower environmental impact than an equivalent cast-in-place reinforced concrete structure in 10 of 11 impact categories. Most significantly, the timber building has a 71% lower GWP. The GWP of the timber building is 126 kg CO<sub>2</sub> eq./m<sup>2</sup> compared to 420 kg CO<sub>2</sub> eq./m<sup>2</sup> for the concrete building. The GWP includes carbon storage of wood as a credit (negative) contribution to GWP. The assessment has a cradle-to-construction site system boundary and uses data from BEES 4.0, the US LCI (life cycle inventory) database, and other sources (Robertson, Lam, & Cole, 2012).



## 42 story hypothetical residential building

When comparing the GWP of a 42-story existing steel and concrete building and the hypothetical hybrid timber structure (2-story concrete podium, upper floors of glulam columns and beams, CLT floors, and steel connections) a SOM study (2013) finds that the cradle-to-site 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 (SOM, 2013). The study does not mention any specific software used to calculate the GWP. The data source for timber products comes from Consortium for Research on Renewable Industrial Materials (CORRIM) reports, and the data source for concrete comes from another study.



## 5 story office building WBLCA (location: United States)

This WBLCA compares eight structural systems for a prototype 5-story office building in Los Angeles: two concrete, two masonry, two steel, and two timber systems. In general, the relative environmental impacts of the timber structural systems are lower than the steel systems, and the impacts of the steel systems are lower than the concrete and masonry. The light frame timber structure has the lowest GWP (4.9 kg CO<sub>2</sub> eq./sf), and the heavy timber structure has a slightly higher GWP (7.4 kg CO<sub>2</sub> eq./sf). The concrete, steel, and masonry structural systems have GWPs that range from 14.5 kg CO<sub>2</sub> eq./sf to 21. kg CO<sub>2</sub> eq./sf. The only environmental impact where the mass (heavy) timber structural systems displays worse environmental impacts is eutrophication. Data source for CLT is not stated (Stringer & Comber, 2015).

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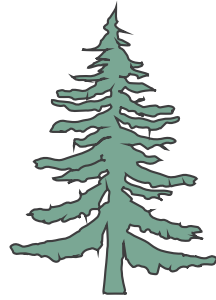
# Reducing CO<sub>2</sub> Emissions from CLT

## Introduction

CLT and other wood products can be a sustainable building material due to their renewable nature and ability to capture carbon dioxide (CO<sub>2</sub>) from the atmosphere, storing it as biogenic carbon (carbon from a biological organism, such as a tree). Although CLT stores carbon, there are carbon dioxide and greenhouse gas emissions associated with a finished CLT panel. Forest practices, transportation, CLT manufacturing, adhesives, sealants, and packaging all result in emissions. Manufacturers and designers can both help to reduce the carbon dioxide emissions from CLT.

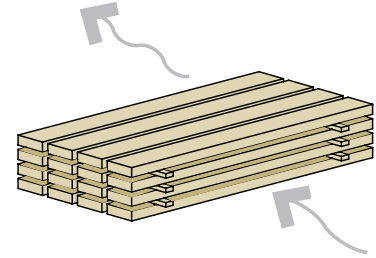
## Principles

Reducing the environmental impacts of CLT generally aligns with recognizable environmental principles: using less material, sourcing local materials, and recycling or reusing resources.



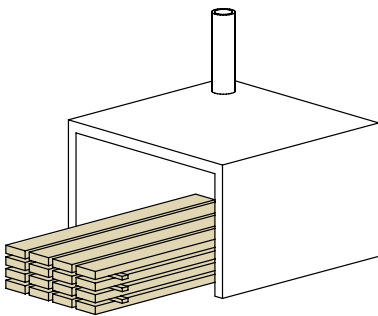
### 1 Lumber Sourcing

Select CLT from forests managed with practices that increase carbon storage and reduce environmental impacts. Longer rotation periods and extended waterway buffers result in a higher average carbon storage at the forest stand level (Diaz, Loreno, Ettl, & Davies, 2018). One way to source environmentally preferable lumber is through sustainable forest management programs such as FSC (Diaz, Loreno, Ettl, & Davies, 2018).



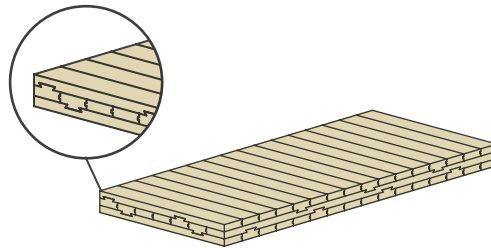
### 2 Air Dry Lumber

Carbon emissions from manufacturing can be reduced by increasing the amount of time lumber is air-dried before being kiln-dried. Increasing air drying time will reduce the amount of energy needed to kiln dry the wood to the correct moisture content. Air drying may require expanded facilities because it takes longer to air dry than kiln-dry wood (Bergman & Bowe, 2007), and may not be feasible in humid climates.



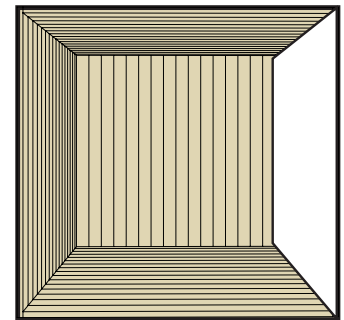
### 3 Upgrade Drying Kilns & Power

Minimize manufacturing CO<sub>2</sub> emissions by upgrading old and inefficient drying kilns. Older technologies can consume up to 1.5 times the amount of energy per thousand board feet when compared to more efficient kilns (Bergman & Bowe, 2007). Providing renewable energy, such as solar, wind, or hydroelectric for kilns and manufacturing will also reduce emissions.



### 4 Use Interlocking CLT

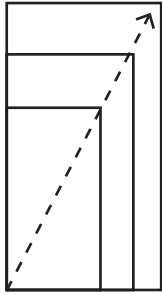
Use interlocking CLT where possible, which does not contain adhesives. In a normal CLT (non-interlocking) panel, environmental impacts include CO<sub>2</sub> emissions from adhesive production and transport. Additionally, adhesives can have negative impacts on air quality through the emission of volatile organic compounds (Smith, 2011).



### 5 Expose CLT Wood

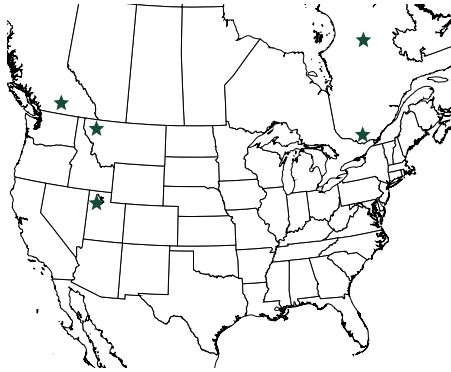
Allow CLT panels to be exposed where possible, without additional materials such as gypsum board or fire treatment. All materials have environmental impacts; thus, it is best to avoid unnecessary materials where possible (Wagh Thistleton Architects, 2018).

# Reducing CO<sub>2</sub> Emissions from CLT



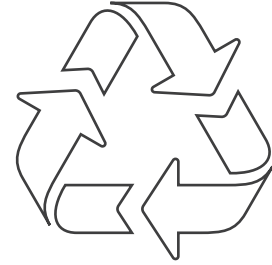
## 6 Design with a Specific Manufacturer's Size

Design with a specific manufacturer's standard panel sizes to reduce material waste and cost. Designing with specific panel sizes may require selecting the manufacturer early in the design process, because manufacturers do not offer consistent sizes (Structurlam, 2016, p. 8). Attempt to use full panels where possible.



## 7 Choose a Regional Manufacturer Using Regional Lumber

To minimize transportation fossil fuel use, select a CLT manufacturer that is closest to the project site. Choose transportation by train or boat if possible. The distance the lumber travels to the manufacturer can also influence the overall emissions. An LCA of CLT production in western Washington found that locally sourcing the lumber and using a lighter wood species could reduce the cradle-to-gate global warming potential by up to 14% (Chen, Pierobon & Ganguly, 2019, p. 15).



## 8 Reuse or Recycle CLT Panels at the End-of-Life

At the end of a building's usable life, reusing or recycling panels (instead of burning for energy or landfilling) is a preferable scenario. The reuse of full panels avoids the energy use and emissions from virgin wood harvesting and manufacturing and the unharvested wood will continue growing and taking carbon from the atmosphere (Sathre & O'Connor, 2010). Chemical treatments of the CLT could reduce the recycling potential (Waugh Thistleton Architects, 2018, p. 86).

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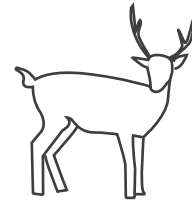
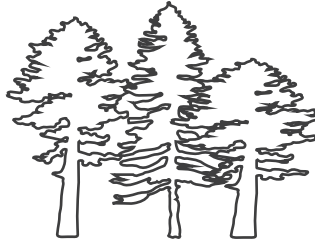
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# CLT & Forests: Knowledge Gaps

## Introduction

The increasing use of CLT and other mass timber products should be coupled with sustainable forest management practices that can help achieve environmental impact and climate change goals, such as maximizing carbon storage. Forest management encompasses numerous variables such as rotation periods, extraction techniques, harvest patterns, and chemical use.



## Transparency & Communication of Forest Management Practices

EPDs communicate the environmental impacts of product such as CLT, but there is currently no standard way to communicate the forest management practices of lumber stands contributing to a product. Certifications such as FSC signal certain forest management practices, but otherwise, practices are not linked to the final product. Forest practices are linked to the carbon storage potential of a forest stand. Extending buffer zones around waterways, increasing intervals of time between harvests (known as rotation periods), and partial harvests are generally recognized means to increase carbon storage in the forest stand (Diaz, Loreno, Ettl, & Davies, 2018, p. 3). Conversely, clear cutting and deforestation are practices with typically negative impacts on carbon storage potential.

### Recommendation

Wood products should include information about average forest management practices of lumber utilized in the product. EPDs could potentially communicate this under an additional information section.

## Climate Change Mitigation and Wood Product Use

Would increasing wood harvesting for mass timber increase or decrease CO<sub>2</sub> emissions? There is disagreement (and uncertainty) about what combination of forest management practices and wood products usage will best maximize carbon storage and minimize greenhouse gas emissions (Fain, 2018). Leakage or substitution effects may reduce the effectiveness of improved forest management practices. Nevertheless, efforts to improve the utilization of harvest (as well as shift from short-lived to long-lived wood products) should be undertaken to improve the climate change mitigation potential of our forests (Smyth et al., 2014). Existing building stock is expected to double by 2050, which could increase wood use beyond sustainable levels if wood is the primary building material. Forests are our most significant carbon sink, and an increase in demand must be coupled with strategic forest management.

### Recommendation

Increased mass timber demand and forest impacts merit further study in all mass timber markets. The impacts of wildfires and potential government legislation on demand could also be considered.

## Biodiversity Implications of Increased Wood Harvesting

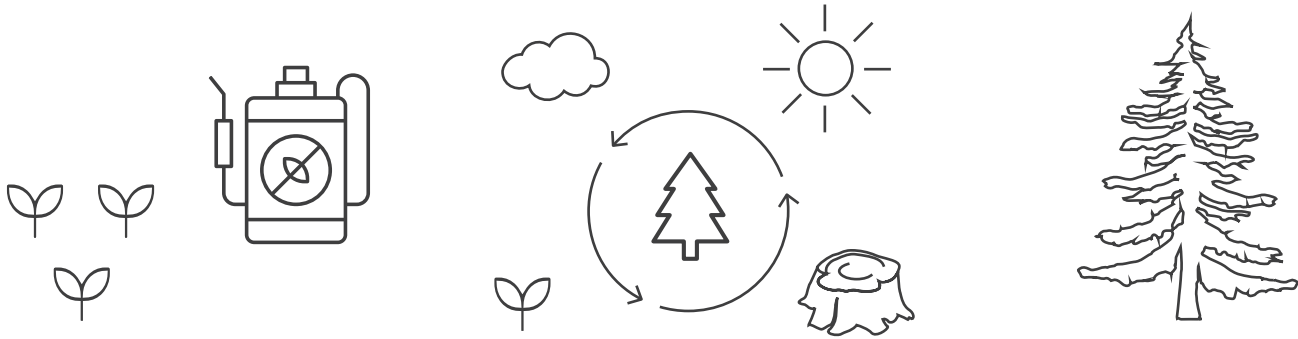
Increasing wood harvesting for CLT and other mass timber products would lead to land use change or increased harvest of existing stands, both of which could affect biodiversity at the level of a stand (alpha biodiversity), local landscape (beta biodiversity), and regional landscape (gamma biodiversity). Biodiversity can be altered by both natural and human disturbances like forest fire suppression or tree harvest (Patel-Weyand, 2002). When trees are harvested, typical rotation periods are shorter than natural disturbance intervals in unmanaged forests and have different biodiversity recovery patterns than natural disturbances (Patel-Weyand, 2002). Encouraging biodiversity at all levels is a key goal of sustainable forestry as defined by the Montreal Process (an international framework for sustainable forestry).

### Recommendation

The biodiversity implications of increased forest harvesting will be linked to where, how, and if more wood is harvested. Variable retention harvest may help improve biodiversity when compared to clear-cutting (Patel-Weyand, 2002). Further research on biodiversity, as well as integration into forest management systems is crucial if the demand for timber products continues to increase.



# CLT & Forests: Knowledge Gaps



## Transparency and Impacts of Pesticide and Fertilizer Use

Although some impacts from pesticides and fertilizers are included within CLT EPDs, the specifics of types and quantities are not stated. Pesticides can damage water quality, animal health, and human health (Coast Range Forest Watch, n.d.). Inert ingredients in pesticide mixes can increase ecotoxicity (developmental neurotoxicity, genotoxicity, and disruption of hormone function) and exposure to pesticides, but are currently not as well-regulated as active ingredients in the United States (Cox & Sorgan, 2006). Although both FSC and SFI support programs to reduce pesticide use, they still allow the use of most chemicals (Mendell & Lang, 2012).

### Recommendation

CLT manufacturers should provide information about forest management practices for their lumber, including use of pesticides and fertilizers. Transparency of chemical use can help designers select a CLT whose wood has required less or no pesticides.

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For remaining sources, see reference list.

## Linking Complex Carbon Models to CLT and Wood Product Use

Life cycle assessments of CLT do not include information about climate change impacts from a full systems perspective. A global understanding of the climate change impacts of CLT and wood products requires complex, integrated biomass carbon models that include biogeophysical factors (surface albedo, surface roughness, and evapotranspiration) and land-use change (direct and indirect) effects (Intergovernmental Panel on Climate Change, 2014, p. 880). Many of these factors are site specific (IPCC, 2014, p. 891), which increases the challenge of implementing such models but potentially offers a way to connect factors to wood products sourced from specific areas.

### Recommendation

Further research and development of complex carbon models is necessary, as well as ways to connect these models to CLT and wood product utilization.

## Stored Carbon Content

50% is an imprecise approximate percentage of wood tissue that is carbon. Wood carbon content varies significantly between species, between different types of tree tissues, and based on environmental conditions (Lamloom & Savidge, 2003; Thomas & Martin, 2012). An assessment of the carbon contents of 41 tree species finds a carbon content range of 46.27% to 49.97% in hardwoods and a range of 47.21% to 55.2% in softwoods (Lamloom & Savidge, 2003). The assumption of 50% carbon content can over or underestimate temperate forest carbon stocks by 6-8% (Thomas & Martin, 2012).

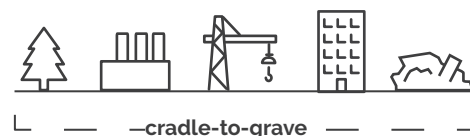
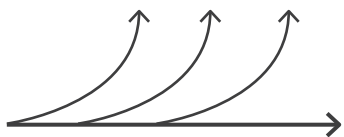
### Recommendation

Tree species-specific carbon content percentages should be the basis for calculating stored carbon content. Creating a robust reference database of the carbon percentages of different tree species is the first step to necessary to move beyond the use of the 50% value. Refining the carbon content values used in environmental product declarations for CLT (and other wood products) should increase the accuracy of carbon sequestration estimates.

# CLT & LCA: Knowledge Gaps

## Introduction

Life cycle assessment (LCA) is a technique used to assess the environmental impacts of a product, such as CLT, at a product and whole building level. LCAs can help estimate the CO<sub>2</sub> emissions of a product's life cycle, but different assumptions about the timing of CO<sub>2</sub> emissions and end-of-life scenarios can lead to varying results. Although some LCA information is available for CLT, additional research on the environmental impacts of CLT finishes, sealants, and connections is necessary to accurately compare with traditional building materials of steel and concrete.



## Timing of Biogenic and Fossil Fuel CO<sub>2</sub> Emissions

In most LCAs, per the guidelines of PCRs, CO<sub>2</sub> emissions and storage are treated as occurring at a single point in time, regardless of their timing within a product life cycle. For CLT and other wood products, this practice leads to an overestimation of biogenic carbon impacts from the burning of wood waste during manufacturing but potentially an underestimation of the benefits from biogenic carbon storage over the lifetime of the product (Skullestad et al., 2016). Proposed dynamic carbon accounting models, such as GWP<sub>bio</sub> (Guest et al., 2013) or Time Zero Equivalent (Salazar and Bergman, 2013), consider the timing of carbon flows, but have not yet been used in CLT LCAs. ISO 14067 *Greenhouse gases - Carbon footprint for products* (2018) allows (but does not require) LCAs to include consideration of timing of carbon flows as additional information.

### Recommendation

CLT manufacturers should consider providing additional information about global warming potential (embodied carbon) calculated using a dynamic carbon model that accounts for timing of carbon emissions and forest rotation lengths.

## CLT Carbon Storage in Landfills

Whether or not CLT exhibits the same decay behavior as other wood products in landfills is relatively unknown. Although the decay of products such as lumber and mdf has been studied, the decomposition of CLT and other mass timber products has assumed to exhibit the same decay rates as lumber. Even for wood and lumber in general, there are a wide range of carbon decay estimates in landfills. WARM, a widely-used tool for calculating end-of-life emissions, assumes that approximately 12% of carbon in dimensional lumber will be emitted, with the remaining 88% being stored (US EPA, 2016, p. 116). WBLCA tools Athena IE and Tally use other decay rates; Athena IE assumes that 23% of wood decomposes, while Tally assumes that 50% of wood decomposes. However, multiple research studies suggest significantly lower landfilled lumber decay rates (De La Cruz, Chanton, & Barlaz, 2013; Micales & Skog, 1996; Ximenes, Brooks, Wilson, & Giles, 2013) or lower decay rates specifically for softwoods typically used in CLT (Wang, Padgett, De La Cruz, & Barlaz, 2011).

### Recommendation

The decay of CLT (and other mass timber products) in landfills should be modeled and verified with excavated samples from active landfills. Continued research on the carbon storage rates of different wood types should be integrated into LCA and WBLCA tools.

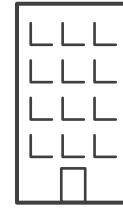
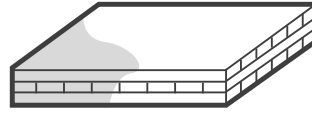
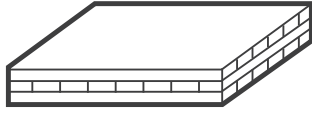
## Life Cycle Data for all Stages

None of the EPDs for North American CLT include full cradle-to-grave life cycle impacts. Omitted stages include stage B (which would include impacts from maintenance, repair, and refurbishment) and stage C (which would indicate the impacts from deconstruction and disposal of a CLT material). Additionally, the assumptions for stage D are not always stated. To understand potential whole-life carbon benefits, all stages need to be considered holistically.

### Recommendation

CLT manufacturers should include all stages of CLT's life cycle in a complete cradle-to-grave EPD if possible, with multiple stage C scenarios, such as landfilling, incineration for bioenergy, and recycling or reuse. EPDs should detail data sources and assumptions for all stages, especially stage D (benefits beyond the system boundary). Stage B impacts could be addressed outside of a CLT EPD with, as CLT is often concealed and generally not expected to be replaced during a building's lifetime.

# CLT & LCA: Knowledge Gaps



## Lack of Life Cycle Assessments (United States)

Although two Canadian CLT manufacturers (Structurlam and Nordic) distribute EPDs for their CLT products (FPInnovations, 2013, 2018), there currently is only an LCA study (not a formal EPD) for one United States manufacturer. Architects and stakeholders in the United States will benefit from this manufacturer transparency when making optimal sourcing decisions for CLT projects. This information will also aid in design comparisons of CLT with traditional building materials.

### Recommendation

CLT manufacturers based in the United States should prioritize the development of environmental product declarations for their CLT products and could consider having multiple EPDs for different wood species or forest sources. EPDs could also include additional information about forest management practices.

## Impacts of CLT Sealants, Finishes & Metal Connections

Information on the environmental impacts of available sealants and finishes for CLT is generally not listed on CLT manufacturers' websites or EPDs. Documentation of the environmental impacts of screws, plates, and connections is also generally absent. In a WBLCA, omissions of these impacts can lead to an underestimation of environmental impacts resulting from CLT building systems.

### Recommendation

CLT manufacturers should display or provide links to information about possible sealants, finishes, and connections including within environmental product declarations. They should also ensure that the optional impacts of finishes and connections are available within prominent WBLCA tools, such as Tally or Athena IE.

## Whole Building Life Cycle Assessment (WBLCA) & CLT data

LCA data used for CLT in a whole building life cycle assessment is not always transparently stated, or may not be specific to CLT. For instance, many existing WBLCA use data from glulam or lumber in general, instead of CLT. This imprecision could lead to inaccuracies. Luckily, WBLCA softwares are beginning to integrate CLT LCA data as it becomes available (i.e. Tally includes two CLT options - a generic CLT or CLT from the manufacturer KLH).

### Recommendation

CLT data used for whole building life cycle assessments should come from the actual CLT EPDs, where possible. WBLCA tools should also strive to increase transparency of life cycle data for CLT and all materials.

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