

CLT Handbook

CROSS-LAMINATED TIMBER

U.S.  EDITION

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The U.S. Edition of the CLT Handbook: cross-laminated timber can be electronically downloaded without charge from the website www.masstimber.com. Additional information can be obtained by visiting the websites of FPInnovations, USFPL, American Wood Council (AWC), APA and U.S. WoodWorks. Hard copies can be obtained through AWC (www.awc.org).

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FC Handbook

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U.S.  EDITION

Edited by
Erol Karacabeyli, P.Eng., FPInnovations
Brad Douglas, P.E., AWC

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PREFACE

Expansion into mid-rise, high-rise and non-residential applications presents one of the most promising avenues for the North American wood industry to diversify its end use markets. This may be achieved by:

- Designing to new building heights with **Light Frame Wood Construction**
- Revival of **Heavy Timber Frame Construction**
- Adoption of **Cross-laminated Timber (CLT)**
- Facilitating **Hybrid Construction**

There are concerted efforts both in Canada and in the United States towards realizing that goal. In fact, the Canadian provinces of British Columbia and Quebec went even further and created specific initiatives to support the use of wood in those applications.

This Handbook is focused on one of these options – adoption of cross-laminated timber (CLT). CLT is an innovative wood product that was introduced in the early 1990s in Austria and Germany and has been gaining popularity in residential and non-residential applications in Europe. The Research and Standards Subcommittee of the industry’s CLT Steering Committee identified CLT as a great addition to the “**wood product toolbox**” and expects CLT to enhance the re-introduction of wood-based systems in applications such as 5- to 10-story buildings where heavy timber systems were used a century ago. Several manufacturers have started to produce CLT in North America, and their products have already been used in the construction of a number of buildings.

CLT, like other structural wood-based products, lends itself well to prefabrication, resulting in very rapid construction, and dismantling at the end of its service life. The added benefit of being made from a renewable resource makes all wood-based systems desirable from a sustainability point of view.

In Canada, in order to facilitate the adoption of CLT, FPInnovations published the Canadian edition of the CLT Handbook in 2011 under the Transformative Technologies Program of Natural Resources Canada. The broad acceptance of the Canadian CLT Handbook in Canada encouraged this project, to develop a U.S. Edition of the CLT Handbook. Funding for this project was received from the Binational Softwood Lumber Council, Forestry Innovation Investment in British Columbia, and three CLT manufacturers, and was spearheaded by a Working Group from FPInnovations, the American Wood Council (AWC), the U.S. Forest Products Laboratory, APA-The Engineered Wood Association and U.S. WoodWorks. The U.S. CLT Handbook was developed by a team of over 40 experts from all over the world.

Both CLT handbooks serve two objectives:

- Provide immediate support for the design and construction of CLT systems under the alternative or innovative solutions path in design standards and building codes;
- Provide technical information that can be used for implementation of CLT systems as acceptable solutions in building codes and design standards to achieve broader acceptance.

The implementation of CLT in North America marks a new opportunity for cross-border cooperation, as five organizations worked together with the design and construction community, industry, universities, and regulatory officials in the development of this Handbook. This multi-disciplinary, peer-reviewed CLT Handbook is designed to facilitate the adoption of an innovative wood product to enhance the selection of wood-based solutions in non-residential and multi-storey construction.

Credible design teams in different parts of the world are advocating for larger and taller wood structures, as high as 30 stories. When asked, they identified the technical information compiled in this Handbook as what was needed for those applications.

A Renaissance in wood construction is underway; stay connected.

ACKNOWLEDGEMENTS

The great challenge with this U.S. Edition of the CLT Handbook was to gather experts from the United States, Canada and Europe to bring together their expertise and knowledge into a state-of-the-art reference document. The realization of this Handbook was made possible with the contribution of many people and numerous national and international organizations.

Such a piece of work would not be possible without the support from financing partners and, as such, we would like to express our special thanks to Binational Softwood Lumber Council, Forestry Innovation Investment (FII), Nordic Engineered Wood, Structurlam, and CLT Canada for their financial contribution to this project.

First and most of all, we would like to express our gratitude to AWC, APA, USFPL, FPInnovations, U.S. WoodWorks and their staff for providing the effort and expertise needed to prepare this work. We would also like to express our special thanks to all chapter authors, co-authors, and reviewers who shared their precious time and expertise in improving this manual.

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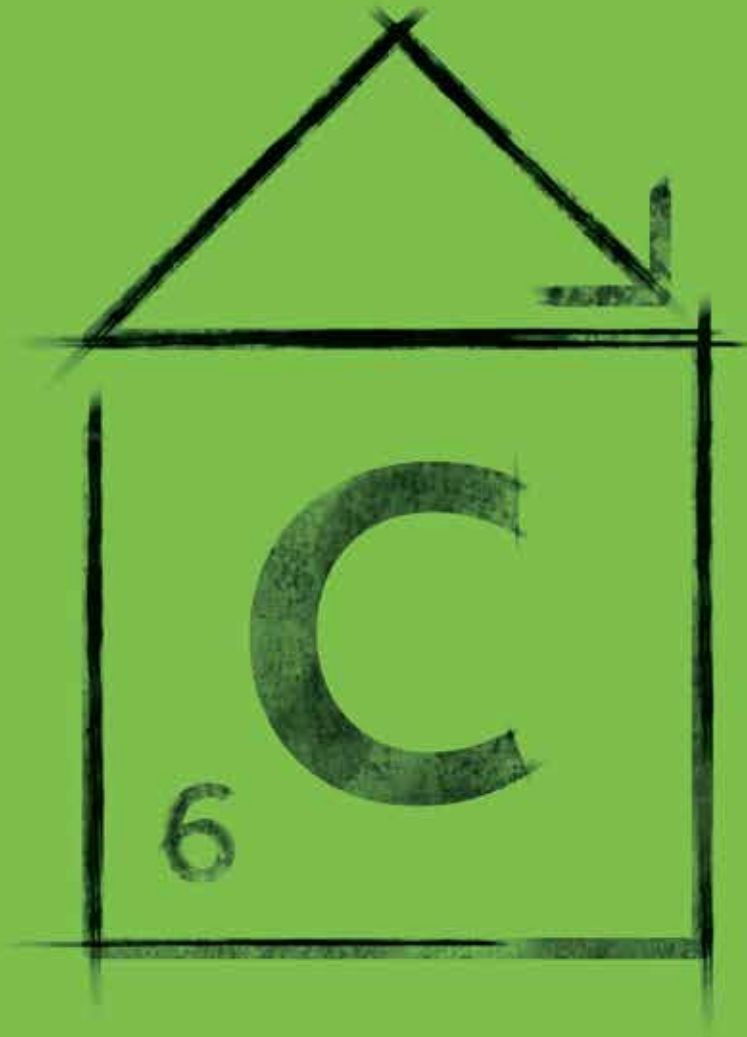
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CONTENTS

CHAPTER 1	Introduction to cross-laminated timber
CHAPTER 2	Cross-laminated timber manufacturing
CHAPTER 3	Structural design of cross-laminated timber elements
CHAPTER 4	Lateral design of cross-laminated timber buildings
CHAPTER 5	Connections in cross-laminated timber buildings
CHAPTER 6	Duration of load and creep factors for cross-laminated timber panels
CHAPTER 7	Vibration performance of cross-laminated timber floors
CHAPTER 8	Fire performance of cross-laminated timber assemblies
CHAPTER 9	Sound insulation of cross-laminated timber assemblies
CHAPTER 10	Building enclosure design for cross-laminated timber construction
CHAPTER 11	Environmental performance of cross-laminated timber
CHAPTER 12	Lifting and handling of cross-laminated timber elements



Environmental

Environmental performance
of cross-laminated timber

CHAPTER 11

Authors

Jennifer O'Connor, M.Arch., FPIInnovations
Lisa Podesto, M.S., P.E., WoodWorks
Alpha Barry, Ph.D., MBA, FPIInnovations
Blane Grann, M.Sc., FPIInnovations

Peer Reviewers

Kenneth Bland, P.E., American Wood Council
Liv Haselbach, Ph.D., P.E., LEED-AP BD+C, Washington State University

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The U.S. Edition of the CLT Handbook: *cross-laminated timber* combines the work and knowledge of American, Canadian and European specialists. The handbook is based on the original Canadian Edition of the CLT Handbook: *cross-laminated timber*, that was developed using a series of reports initially prepared by FPInnovations and collaborators to support the introduction of CLT in the North American market. A multi-disciplinary team revised, updated and implemented their know-how and technologies to adapt this document to U.S. standards.

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ABSTRACT

The environmental footprint of CLT is frequently discussed as potentially beneficial when compared to functionally equivalent non-wood alternatives, particularly concrete systems.

In this Chapter, the role of CLT in sustainable design is addressed. The embodied environmental impacts of CLT in a mid-rise building are discussed, with preliminary results from a comprehensive life cycle assessment (LCA) study.

We also discuss other aspects of CLT's environmental profile, including impact on the forest resource and impact on indoor air quality from CLT emissions. The ability of the North American forest to sustainably support a CLT industry is an important consideration and is assessed from several angles, including a companion discussion regarding efficient use of material. Market projections and forest growth-removal ratios are applied to reach a clear conclusion that CLT will not create a challenge to the sustainable forest practices currently in place in North America and safeguarded through legislation and/or third party certification programs.

To assess potential impact on indoor air quality, CLT products with different thicknesses and glue lines were tested for their volatile organic compounds (VOCs) including formaldehyde and acetaldehyde emissions. CLT was found to be in compliance with European labeling programs as well as the most stringent CARB limits for formaldehyde emissions. Testing was done on Canadian species, as there was no U.S. supplier of CLT at the time of this writing; because VOC emissions are affected by species, this work should be repeated for products made from different species.

TABLE OF CONTENTS

Acknowledgements	ii
Abstract	iii
1 Introduction	1
2 Life Cycle Environmental Impacts of a CLT Mid-rise Building	2
2.1 Description of the LCA Study	2
2.2 Results	3
3 Potential Indoor Air Quality Impacts of Using CLT in Buildings	8
4 Resource Assessment: Impact of CLT on the Forest	9
5 Potential Contribution of CLT to Green Building Objectives	13
6 Material Disclosure	16
7 Conclusions	17
8 References	18
Appendix A: Literature Review	22
A1 Literature Review on Environmental Performance of CLT	22
Appendix B: Details on the Mid-rise LCA Study	24
B1 Objective and Method	24
B1.1 Life Cycle Inventory	26
B2 Results	29
B2.1 Assumptions and Limitations	30
B2.2 Sensitivity	31
B3 Discussion	32
B3.1 End-of-life Scenarios	32
B3.2 Carbon Storage	32
Appendix C: Details of the VOC Testing	34
C1 Objectives and Background	34

C2	Procedures and Results	34
	C2.1	Materials Sampling, Packaging, Transportation and Conditioning 34
	C2.2	Method 35
	C2.3	Quantification of Formaldehyde 38
	C2.4	Quantification of the TVOC 38
C3	Results and Discussions	38
C4	Conclusions and Recommendations	45

List of Tables

- Table 1* Material disposal assumptions 28
- Table 2* Absolute values for total life cycle impacts 29
- Table 3* Small chamber operating conditions 36
- Table 4* TDU/GC/MS and HPLC operating conditions 37
- Table 5* Samples 24-hour individual VOCs (iVOCs), TVOC as toluene, between n-C6 and n-C16 including formaldehyde ($\mu\text{g}/\text{m}^3$) 39
- Table 6* Samples 24-hour individual VOCs (iVOCs), TVOC as toluene, between n-C6 and n-C16 including formaldehyde ($\mu\text{g}/\text{m}^3$) 40
- Table 7* Example of some European emission labeling systems 42
- Table 8* Samples 24-hour iVOCs, TVOC as toluene, between n-C6 and n-C16 emission factors including formaldehyde ($\mu\text{g}/\text{m}^2\cdot\text{h}$) 43
- Table 9* Samples 24-hour iVOCs, TVOC as toluene, between n-C6 and n-C16 emission factors including formaldehyde ($\mu\text{g}/\text{m}^2\cdot\text{h}$) 44
- Table 10* 24-hour formaldehyde emissions as a function of product types 45

List of Figures

- Figure 1* Preliminary LCA results – relative life cycle impacts, excluding operational phase and equivalent building components, broken down by life cycle stage 4
- Figure 2* Results normalized to total U.S. results from 1999 using data from Bare, Gloria & Norris (2006) 6
- Figure 3* Growth-removal ratios by softwoods and hardwoods, 1952-2006 11
- Figure 4* Certified forest area in North America as of August 2012 12
- Figure 5* System boundary 25
- Figure 6* Picture showing a prepared sample with edges sealed ready to be put in the chamber 35
- Figure 7* A general view of the 1 m³ environmental chamber used for emissions testing 36
- Figure 8* 24-hour VOCs including formaldehyde and acetaldehyde off gassing as a function of samples types 40
- Figure 9* 24-hour VOCs including formaldehyde and acetaldehyde off gassing as a function of samples types 41
- Figure 10* 24-hour TVOC emissions as a function of cross-laminated products 41

1

INTRODUCTION

The environmental footprint of CLT is frequently discussed as beneficial. This Chapter considers the criteria for determining environmental performance of CLT systems; we also quantify that performance where possible.

Environmental expectations for CLT would align with common sustainable design objectives. For example, some questions that might be asked of CLT include:

- What are the embodied life cycle assessment impacts of CLT buildings?
- Does CLT adversely affect indoor air quality?
- Does it minimize the use of materials?
- Does it reduce operating energy in buildings?
- Does it contain recycled material?
- Is there enough forest to sustainably support manufacturing?

This is not an exhaustive list of sustainability criteria but a good starting point. In this Chapter, we address in detail the questions of embodied effects, indoor air quality and forest resource. Specific embodied effects examined include consumption of material and energy resources, creation of solid wastes, and life cycle assessment impact measures such as global warming potential, acidification potential and eutrophication potential. We touch on other topics throughout the Chapter and in our closing remarks.

As we will show in this Chapter, the attributes of CLT construction systems are consistent with some important sustainable design criteria.

2

LIFE CYCLE ENVIRONMENTAL IMPACTS OF A CLT MID-RISE BUILDING

One of the most valuable tools for measuring environmental impacts of a product or process is life cycle assessment (LCA). LCA is a scientific technique, guided by international standards, to measure flows between a product and nature and to assess the impact of those flows in categories such as global warming potential, acidification potential and smog potential.

Manufacturers use LCA to identify environmental hot spots in the life cycle of their products so that improvements can be sought. In addition, if LCA data exists for most construction products, designers can perform an LCA for whole buildings and compare impacts of different material decisions. Publically-available LCA data also helps meet a potential market demand for environmental disclosure from manufacturers inspired, for example, by the LEED® program.

An LCA for North American CLT has been published (Athena Sustainable Materials Institute, 2012b). This product information allows us to calculate various embodied impacts of a CLT building. In this section, we provide preliminary findings for a LCA study of a mid-rise CLT building, which are to be published in a comparative building LCA by FPIinnovations in 2013. The intended use of the results in a comparative LCA leads to the exclusion of several building components from the analysis which were deemed to be identical between the CLT building and the building it will be compared with. Building components excluded from this study include: foundation walls, windows, doors, plumbing, electrical, hand railings, and HVAC equipment. Please see Appendix B for full details of the assessment method for these preliminary results.

2.1 Description of the LCA Study

The LCA study was performed on an existing CLT apartment building located in Québec, Canada. The building is 43,700 square feet in area (4,060 square meters) and has four stories plus one underground level. A brief overview of the study along with results and discussion are provided below. Refer to Appendix B for additional information on the methodology, assumptions, limitations, parameter sensitivity and additional discussion.

The Athena Impact Estimator for Buildings is an LCA-based modeling tool that was used in this analysis, along with additional methods to address gaps in the Impact Estimator. The Impact Estimator provides cradle-to-grave LCA results; in other words, it includes the impacts of resource extraction and material production, construction,

maintenance and replacement, demolition, and associated transport processes. In this study, the building lifetime is assumed to be 60 years. Operating energy is not included in the assessment, in order to better isolate the embodied impacts of the materials.

The Impact Estimator draws on embedded LCA databases for materials, construction processes, maintenance and replacement activities, transportation and energy. Because CLT systems are not yet included in the Impact Estimator, additional LCA resources had to be applied to this analysis. Specifically, this study augmented Impact Estimator results using data from a published LCA study for the CLT product that was used in this building (Athena Sustainable Materials Institute, 2012b).

The Impact Estimator produces a subset of results according to a common North American impact assessment method known as TRACI¹. These impact categories from TRACI include:

- Global Warming Potential (GWP measured in kg of CO₂ equivalent)
- Acidification Potential (AP measured in moles of hydrogen ion (H⁺) equivalents)
- Respiratory Effects (RE measured in kg of particulate matter (PM) up to 10 microns)
- Eutrophication Potential (EP measured in kg nitrogen (N) equivalent)
- Ozone Depletion Potential (OD measured in kg chlorofluorocarbon-11 (CFC-11) equivalent)
- Smog Potential (measured in kg of ozone (O₃) equivalent)

The Impact Estimator excludes TRACI impacts for human toxicity and ecotoxicity, which are listed as optional measures in ISO 21930 (2007) due to greater uncertainty in these measures. Fossil fuel consumption is also an indicator category used by the Impact Estimator which refers to non-renewable fossil fuel energy consumption plus feedstock fossil fuel² and includes direct and indirect energy use along the supply chain.

2.2 Results

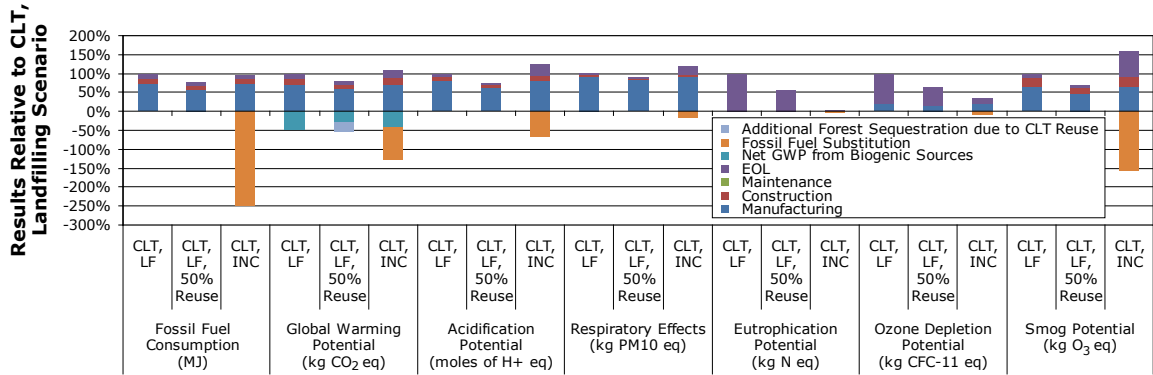
LCA results are best used to help guide decisions with an understanding that there is always uncertainty in an estimate of future states. For example, end-of-life assumptions can make a difference in the results for wood. Two end-of-life scenarios are included for both buildings to consider; landfilling and incineration. An additional scenario was considered for a second generation CLT building where 50% of the CLT panels are assumed to be from reused sources and 50% of the CLT panels are kept out of the landfill at the end-of-life for future reuse.

LCA results for the CLT building are given in Figure 1 normalized to the total emissions from the scenario where landfilling is used to dispose of un-recycled materials and no CLT panels are reused. In the following paragraphs, the results for each impact category are discussed. Following this, the results are presented normalized to total per capita U.S. emissions in 1999 to help contextualize the magnitude of the results.

In Figure 1, benefits from substituting the energy content of forest products for fossil fuel in the incineration scenario are kept separate from total impacts to differentiate between actual emissions and avoided emissions which, by definition, never physically exist. The net GWP benefit from wood products is also presented separately while detailed contributions from end-of-life and forest regrowth are discussed in the GWP section.

¹ U.S. EPA's Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI) 2.0 (Bare, 2011).

² Feedstock energy refers to the energy content of the material.



Note: Two end-of-life scenarios were modeled: landfilling (LF) and incineration (INC). In addition, a scenario is shown where 50% reclaimed CLT panels are used for the building and 50% of the panels are sent for reuse when the building is demolished. Results are presented relative to the landfilling scenario with no reused panels. Given that these results are intended to be used in a comparative building LCA published by FPInnovations in 2013, the system boundary excludes operational energy consumption, fenestration, foundation elements and other elements identified in Appendix B, as these elements were deemed equivalent between the building intended for comparison.

Figure 1

Preliminary LCA results – relative life cycle impacts, excluding operational phase and equivalent building components, broken down by life cycle stage

Fossil Fuel Consumption

Fossil fuel consumption is dominated by the material manufacturing stage. For the scenarios without reused panels, less than 8% of the emissions from the material manufacturing stage are due to transportation. Floors represent roughly 50% of fossil fuel consumption from the manufacturing stage which is almost exclusively from CLT production. When looking at CLT production, roughly 45% of fossil fuel use comes from the manufacturing of CLT while another 50% is from the rough dry lumber. When landfilling is used to dispose of un-recycled materials at the end-of-life, the same building made with 50% reused CLT panels allows for a 2% reduction in fossil fuel consumption. Relative to the modeled system, we also see that using wood products to produce heat at the end-of-life allows for the displacement of a significant quantity of fossil fuel use.

Global Warming

As the emissions driving GWP largely result from fossil fuel consumption, it is not surprising to find similar comparative results for GWP and fossil fuel consumption. We see significant potential for avoiding emissions in the incineration scenario when wood is used to produce energy at the end-of-life and substitute for natural gas use.

For the two scenarios not using reused CLT panels, the avoided GWP (-583 metric tons CO₂ eq) as carbon is re-sequestered during forest re-growth on the harvested land more than offsets the GWP from landfilling with no reused panels (452 metric tons CO₂ eq) and the incineration scenario (472 metric tons CO₂ eq). For the landfilling scenario with 50% reused panels, the avoided GWP from forest re-growth is -399 kg CO₂ eq while the landfilling emissions are 249 tons of CO₂ eq. The avoided emissions include the carbon that is re-sequestered on the land that was harvested to provide the wood for the building, but also the additional carbon that can be sequestered from the continued growth of trees that were not harvested due to the use of reused CLT panels if these trees were to continue to mature. Alternatively, this wood could be harvested and used in another building. At the same time, landfilling emissions are decreased in the scenario with reused CLT panels because it is assumed that 50% of the CLT panels are again reused at the end-of-life with less wood ending up in the landfill.

While methane is released when wood is landfilled, a large portion of wood is permanently sequestered so that the net GWP due to biogenic sources for landfilling and incineration is similar over a 100 year period. Appendix B provides additional information regarding end-of-life modeling.

Acidification

Emissions resulting in acidification were highest for the incineration scenario due to additional stack emissions. However, we also see a significant potential for avoiding acidification when the heat from wood incineration is used to displace natural gas use in a boiler. The potential for significant reductions in acidification are also found in a building with 50% reused CLT panels due to the high share of total acidification emissions which are due to CLT, the primary building material.

Respiratory Effects

Respiratory effects are similar across scenarios as the driver for these emissions are spread across the material manufacturing stage of several materials including gypsum, rebar, and concrete, and to a lesser extent mineral wool and CLT. While the combustion of wood products to produce heat at the end-of-life contributes additional particulate emissions, a large portion of these are offset by the direct and indirect emissions from avoided natural gas use.

Eutrophication

Eutrophication emissions result almost exclusively from the landfilling of wood products. Given that landfilling emissions and impacts are very site specific, results from eutrophication should be interpreted with caution. The landfill modeling undertaken in Simapro v7.3.3 using ecoinvent v2.2 data allows for the exclusion of long-term (> 100 year) emissions which results in a reduction in eutrophication emissions by a factor of over 100. The uncertainty involved in modeling the fate and impacts of long-term emissions suggests the need for further caution when interpreting these results. It is possible that the low levels of the emissions driving eutrophication over a long period of time will have minor negative impacts.

Ozone Depletion

Ozone depleting emissions also result mainly from landfilling. However, since ozone depleting emissions are shown below to be trivial when normalized to per capita yearly emissions in the United States, they are not discussed further.

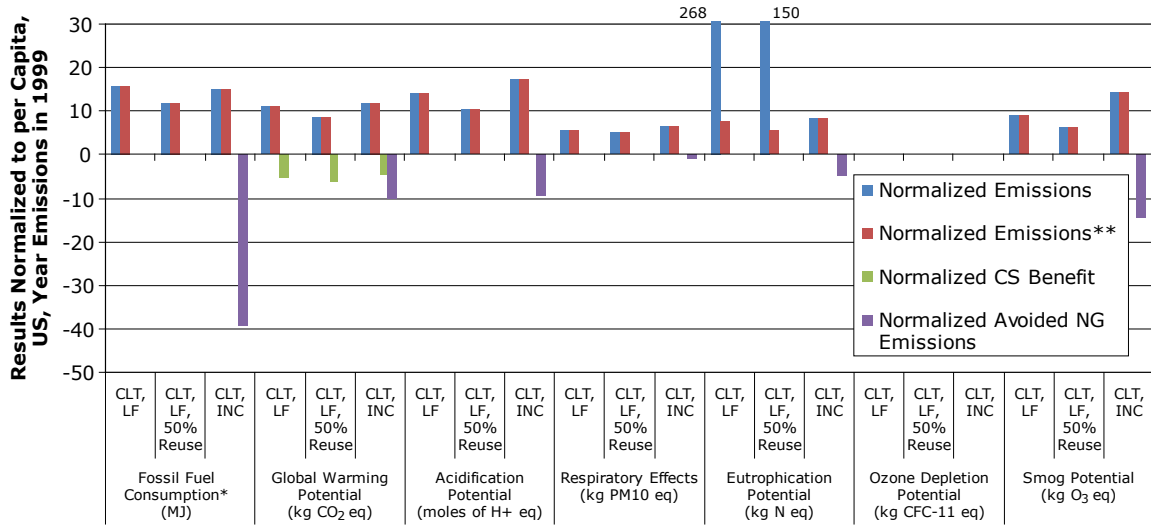
Smog

Significant smog emissions occur across life cycle stages. At the end-of-life, smog emissions are mainly from the incineration of wood, but also from grinding up concrete and chipping wood. During the construction stage, smog emissions are almost exclusively from the transport of materials to the construction site of which the 310 miles (500 km) CLT transport is dominant. During the manufacturing stage, smog emissions result from CLT production, the production of concrete and rebar for the footings, as well as from gypsum and mineral wool production.

Normalization to Per Capita U.S. Emissions in 1999

Normalizing the environmental indicators of an LCA to total yearly per capita levels is useful for determining the significance of different impact categories. In Figure 2, results from this study are normalized to per capita U.S. emissions in 1999 using data from Bare, Gloria & Norris (2006) and the World Bank (2012). Noticeably long-term eutrophication emissions are quite high. Issues with this indicator have been addressed above. While ozone depleting emissions are relatively minor, other impact categories are equivalent to between 5 and 15 yearly per capita U.S. levels in 1999. Relative to the 20 odd apartment suites in the building, these normalized figures are small. However, the clean hydroelectricity sources in Québec that underpin the production of locally produced manufactured goods heavily influenced the results from this study. Normalizing GWP emissions (positive emissions in the graph) for the CLT building with landfilling to per capita GHG emissions in Québec in 2009, for example, is equivalent to 27 compared to around 10 in Figure 2³.

³ Per capita greenhouse gas emissions in the Province of Québec were 10.4 metric tons CO₂ equivalent in 2009 (ministère des Finances du Québec, 2012).



NB: CS = carbon sequestration; NG = natural gas

*Normalization values for fossil fuel consumption from World Bank (2012).

**Normalization excludes long-term emissions (>100 years) from landfill degradation.

Figure 2

Results normalized to total U.S. results from 1999 using data from Bare, Gloria & Norris (2006)

With the growing importance of global warming in environmental discussions, it is useful to discuss the carbon aspects of this analysis. The LCA study to be published by FPInnovations in 2013 will discuss the concept of a potential carbon offset value for CLT substitution. A carbon offset is also known as greenhouse gas displacement; it refers to the greenhouse gas emissions avoided by choosing an alternate practice over standard practice. Mid-rise buildings in Québec are not typically made with wood systems, therefore the use of wood in that application would be considered an alternate practice. In that context, if CLT results in reduced greenhouse gas emissions compared to standard practice, one could quantify the greenhouse gas displacement. Such a displacement is a permanent and cumulative benefit for climate change mitigation.

Carbon storage is an important attribute of long-lived wood products like structural components. The carbon in wood comes from carbon dioxide which was removed from the atmosphere by the tree as it grew. While this carbon returns to the atmosphere over the long term, completing the natural carbon cycle, the temporary storage in wood products allows additional CO₂ to be removed from the atmosphere during the building lifetime through the re-growth of trees. Wood products are not a permanent greenhouse gas removal mechanism; however, the temporary carbon storage in wood products can be reasonably considered a carbon credit, depending on time frame and end-of-life assumptions. This reasoning largely stems from the current urgency around climate change, where any delay in carbon emission is helpful in “buying time” to find mitigation solutions to climate change.

For traditional wood structural systems, the carbon mass of wood is relatively small compared to the carbon emissions avoided by using wood instead of steel or concrete (Sathre, O’Connor, 2010). Therefore, an important focus in the use of wood to combat climate change is to increase our rate of wood substitution for other materials, with less emphasis on carbon storage. With CLT, the relationship is the opposite: the carbon mass of wood is quite large compared to the avoided emissions of alternate materials. In this case, there is an interest in putting a value on that stored carbon, with a motivation to keep the carbon in service for as long as possible, and to capture the energy value of that carbon to replace fossil fuel at the end of service life. In total, the wood content of the

modeled CLT building equates to about 951 metric tons of CO₂. To put this amount in context, 951 metric tons of CO₂ are emitted in one year of driving 186 cars⁴.

It is important to recognize that the carbon profile of wood construction and any claimed carbon benefits rely on an assumption of sustainable forest management, such that long-term carbon stocks in forests do not decline due to the use of wood products; see the section on forest resource implications of CLT for discussion on that topic. In addition, note that carbon accounting with regards to wood and forestry is complex, as further discussed in Appendix B.

As a prefabricated product, CLT has good potential for recovery at the end of a building's service life for use in another building. Reusing CLT panels reduces GWP by 263 metric tons of CO₂ equivalent when the end-of-life scenarios include landfilling by reducing production and transport emissions and prolonging the release of stored carbon to the atmosphere.

⁴Conversion to cars was calculated using the U.S. EPA Greenhouse Gas Equivalencies Calculator, <http://www.epa.gov/cleanenergy/energy-resources/calculator.html>.

3

POTENTIAL INDOOR AIR QUALITY IMPACTS OF USING CLT IN BUILDINGS

In this section, we provide preliminary findings regarding emissions to indoor air from cross-laminated timber. This data applies to CLT made from two Canadian wood species, which is the only North American CLT commercially available at the time of this writing. Note that wood product emissions are species-specific, and these test results may not apply to products made from different manufacturers.

As regulatory and non-governmental organizations (NGOs) address indoor air quality issues, they tend to focus on volatile organic compounds (VOCs), including formaldehyde, as key factors relating to the discomfort reported by people working or living inside “air tight” buildings. For wood products, VOCs and specifically formaldehyde are of interest in products containing adhesives, which can be associated with emissions.

In this work, CLT samples were examined for VOC emissions in the FPInnovations laboratory, following applicable test method standards. Please see Appendix C for details on the test methods and the results.

Five CLT products were tested for their volatile organic compounds (VOCs), including formaldehyde and acetaldehyde emissions. The tested laminated products had different thicknesses and different numbers of glue lines. Emissions were collected after 24 hours of samples exposure in the environmental chamber. The adhesive used to manufacture the CLT products was a polyurethane glue (Purbond HB E202), while polyurethane Ashland UX-160/WD3-A322 glue was used for finger jointing.

Results did not show any correlation between individual VOCs (iVOCs), including formaldehyde and acetaldehyde, or total VOCs (TVOCs) and the thickness of the cross-laminated timber panel or the number of glue lines. All five products showed very low levels of iVOC (the highest level was observed with alpha-pinene and $340 \mu\text{g}/\text{m}^3$ for TVOC emissions); most of the detected VOCs consisted of terpene compounds that are naturally found in the wood material itself. Therefore, it can be concluded that the CLT tested will have a negligible or zero impact on indoor air quality.

The formaldehyde emission limits set forth by the Californian Air Resource Board (known under the acronym CARB Phase I and Phase II) are some of the most rigorous emission limits in the United States for wood composite products and have been in effect since July 1st, 2012. Results reported here show that the CLT samples tested easily meet the most stringent CARB limits.

In addition, the results for the five samples were generally lower than limits set forth by European emission labeling systems. In fact, the 24-hour CLT test results were lower than European limits intended for measurement after three days.

Please see Appendix C for details and further results.

4

RESOURCE ASSESSMENT: IMPACT OF CLT ON THE FOREST

When compared to traditional light-frame construction, CLT may appear to be at odds with one of the cornerstones of sustainable design—the efficient use of materials—potentially increasing the volume of wood used in a project substantially. We will discuss the topic of material efficiency later in this Chapter. In this section, we discuss the ability of North American forests to accommodate the use of a product that appears to consume a large amount of wood.

Traditionally, designers have relied on heavy construction materials such as concrete tilt up, steel frames, and composite decking systems to achieve a solid structure with large spans and tall plate heights. Anecdotal information from the WoodWorks⁵ team suggests that designers are increasingly considering the use of a timber alternative because of their perception that timber has carbon benefits when substituted for other materials and a relatively small manufacturing energy input; however, some have questioned whether an increase in demand for lumber will negatively impact our forest resources. If designers in the United States begin to replace construction materials typically used in commercial buildings with mass timber products such as CLT, will we create an unsustainable trend leading to forest resource depletion?

The answer is no. Stringent sustainable forest management practices in the United States and Canada restrict harvesting levels (while additionally maintaining other forest values such as biodiversity and wildlife habitat). Still, CLT users may wonder if a major uptake of CLT would be felt in the forest. In this Section, we use market data to demonstrate hypothetical scenarios; we show how many CLT buildings can easily be accommodated within historic sustainable supply capacity. Note that we do not address the availability of CLT; many other products compete for forest resources. In this exercise, we simply put theoretical CLT consumption in the context of current construction wood usage in order to provide a sense of magnitude of the potential impact of CLT.

In Chapter 1 of this Handbook, an assessment of the market opportunity for CLT was completed whereby the estimated 2015 volume of new construction was overlaid by market segment with the scenarios of CLT capturing both 5% and 15% of that new construction market. If CLT was used for 15% of new multi-residential and non-residential construction projects (1 to 10 stories) built in 2015, there would be a 12% increase in the overall board footage demand over 2011 levels. To put this in perspective, in 2011 the estimated U.S. lumber consumption was 22.6 billion board feet (BBF) (RISI), while in 2005, when the United States was at its peak for lumber demand, it is estimated that 45.5 BBF (RISI) was consumed—a difference of 186%. For the lumber market

⁵ WoodWorks is an initiative of the Wood Products Council established to provide free technical support as well as education and resources related to the design of non-residential and multi-family wood buildings.

to see 2005 levels of demand based on the construction expectations for 2015, CLT would have to comprise over 100% of the multi-residential and non-residential market.⁶

Potential impact on total consumption can be explored deeper in the context of a prototypical CLT building. The Stadthaus project in the United Kingdom is an eight-story, 24,000 square foot CLT structure, built over one story of concrete with 29 residential units and an office. This structure is one of the tallest modern timber structures in the world and includes an estimated 33,500 cubic feet (950 cubic meters) of timber (Waugh, 2009).

CLT is not currently being commercially produced in the United States for structural purposes, however domestic interests are high and the U.S. wood industry anticipates some local production by 2015. As such, it is pertinent to explore the effects of CLT use on U.S. forests. In 2006, 9.86 billion cubic feet of softwood lumber was harvested from U.S. forest lands, which means the lumber harvested for wood products in 2006 in the United States alone could build over 295,000 CLT structures equivalent in volume to the Stadthaus project or 7.06 billion square feet of CLT projects with equivalent density (cubic feet of timber/square foot of floor area).⁷

While the Stadthaus example may seem irrelevant because CLT construction would not replace current wood construction but rather represent additional demands, let's put this in another context. The 2012 demand for wood products is down more than 45% (RISI) from 2006 levels. Consider that, in addition to domestic supply, the United States imports on average 25-33% (RISI) of its wood supply from Canada. Because we know that the 2006 level of production did not adversely affect the domestic or Canadian standing inventory, it is plausible that, based on forecasts for 2012 U.S. construction, North American forests could accommodate over 176,696 CLT structures equivalent in volume to the Stadthaus project (or 4.24 billion square feet) in addition to the current demands for light-frame wood products.⁸

North American forestry has a proven record of maintaining the standing forest. Figure 3 shows the growth-removal ratios (growth/harvest) for U.S. forests in recent history. Since 1952, the growth-removal ratios for both softwood and hardwood demonstrate that growth has exceeded harvest and the United States has not been depleting its forest resources from a timber volume standpoint, even during periods of high demand. In 2006, when 1.7% of the standing volume of the forest was harvested (Smith et al., 2009; Table 17) and the United States produced 45.5 BBF of lumber (RISI), forest growth still exceeded harvest by close to 1%.

⁶ As previously noted, there are many end uses for forest resources, all of which may compete for a finite supply of raw materials depending on market economics. Should U.S. housing starts ever return to 2005 peak levels and thereby once again create a large demand for framing lumber, restricted supply of raw resources and the resulting effect on market prices may affect the availability of raw resources for CLT production. The current example is not meant to suggest that enough CLT would necessarily be available for building 100% of all multi-residential and non-residential buildings.

⁷ Again, this example is simply provided to convey a concept of scale, and to illustrate the vast number of CLT buildings that could be erected if all lumber supply were directed to this use.

⁸ Calculated based on the following:

- Volume of softwood lumber harvested in the United States in 2006 = $9.86 \times 10^9 \text{ ft.}^3$
- Estimated total volume of North American lumber consumed in 2006 (based on 25% historical Canadian imports) = $13.15 \times 10^9 \text{ ft.}^3$
- Estimated volume of softwood lumber harvested in the United States in 2012 = $5.42 \times 10^9 \text{ ft.}^3$
- Estimated total volume of North American lumber consumed in 2012 (based on 25% historical Canadian imports) = $7.23 \times 10^9 \text{ ft.}^3$
- Estimated volume of CLT in Stadthaus project = $33,500 \text{ ft.}^3$
- CLT Plan Square footage of Stadthaus project = $24,000 \text{ ft.}^2$
- Estimated additional capacity available = $(13.15 \times 10^9 \text{ ft.}^3 - 7.23 \times 10^9 \text{ ft.}^3) / 33,500 \text{ ft.}^3 = 176,696$ Stadthaus equivalent structures
- Estimated additional demand capacity available = $176,696 \text{ structures} \times 24,000 \text{ ft.}^2 / 1 \text{ structure} = 4.24 \times 10^9 \text{ ft.}^2$

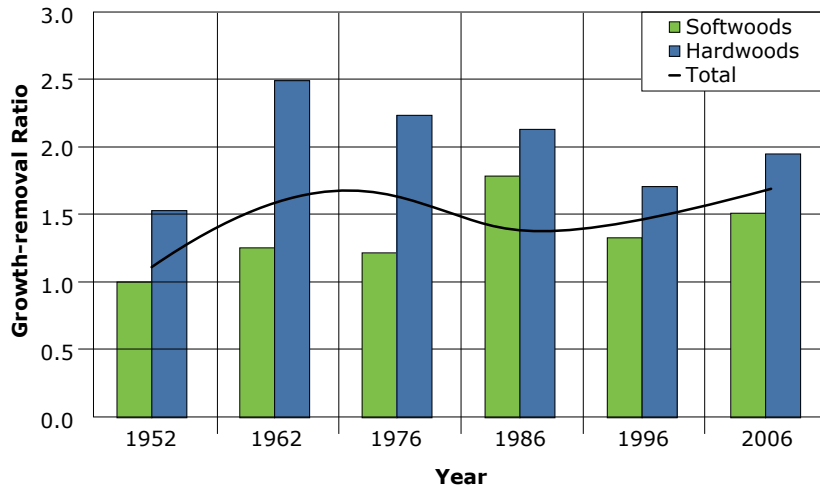


Figure 3
Growth-removal ratios by softwoods and hardwoods, 1952-2006 (Data source: Smith et al., 2009)

Overall, forest standing inventory is affected by more than growth and removal. Forest mortality due to insect, disease and fire also needs to be taken into account. While the mortality rate has been steadily increasing, the overall rate of loss remains less than 1% of the growing stock. This means that the overall standing inventory of softwood and hardwood continues to grow even with harvest and natural mortality factored in. Because CLT has the ability to utilize lower grade dimensional lumber, it also offers an opportunity to utilize a large percentage of forests devastated by insect and disease. CLT offers the possibility for the standing dead wood in such forests to be used in a high value product, financially incentivizing the use of what would otherwise be considered a wasted resource, provided the trees are accessible and near a mill.

Users of any wood products including CLT can be confident that North American forest practices comply with strict harvesting controls. Numerous government and industry publications provide detailed data on an annual basis for the purpose of transparent disclosure to the public about forests, harvesting and forest management. According to “Sustainable Forestry in North America”, a pamphlet that concisely summarizes this data, “there are a large number of federal policies covering U.S. forests, and the State and local legal requirements are also extensive. During the past 50 years, less than 2 percent of the standing tree inventory in the U.S. was harvested each year, while net tree growth was 3 percent.” Note that a portion of wood used in U.S. construction comes from Canada. “In Canada, 93 percent of the forests are publicly owned and forest companies operate under some of the most stringent sustainability laws and regulations in the world. Less than one half of one percent of the managed forest is harvested annually, and the law requires all areas to be promptly regenerated.”⁹

Worldwide, only 10 percent of forests are certified to one or more sustainable forest certification standards. These standards tend to have more similarities than differences and, while there are those who debate the merits of one over another, the real issues of concern—such as deforestation and illegal logging—are occurring in forests that are not certified and located in developing countries with insufficient laws and governing structures to ensure sustainable forest management.

⁹ For these forestry statistics and more information on forest practices in the United States and Canada, see “Sustainable Forestry in North America”, available at www.woodworks.org

As of August 2012, more than 500 million acres of forest in Canada and the United States were certified under one of the four internationally recognized programs used in North America: the Sustainable Forestry Initiative (SFI), Canadian Standards Association’s Sustainable Forest Management Standards (CSA), Forest Stewardship Council (FSC), and American Tree Farm System (ATFS), accounting for approximately 29% of North American forests (SFI, personal communication) (Figure 4). In the United States, the majority of non-certified forests are small (<10 acres) family-owned stands. There typically is no financial incentive for these small-scale operations to obtain third-party certification. A more pressing concern is to ensure these operations continue to maintain forested land—these small family-owned operations account for approximately 60 percent of the wood harvested in the United States—rather than be sold and converted into non-forest uses if there is inadequate financial incentive for productive forestry (Smith et al., 2009).

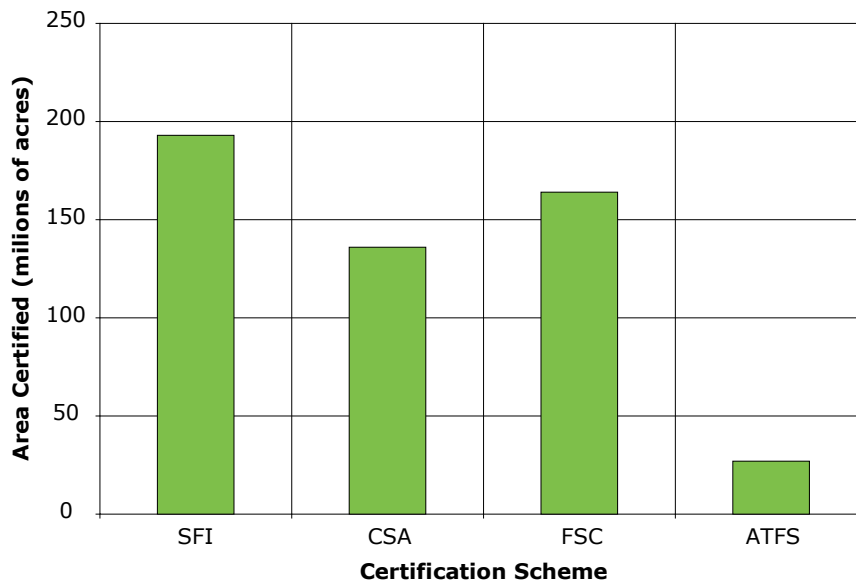


Figure 4
 Certified forest area in North America as of August 2012 (Sources: www.pefc.org, www.fscus.org, www.fscscanada.org, www.fsc.org, www.certificationcanada.org, www.mtc.com.my)

According to Kenneth Skog (personal communication) from the USDA Forest Products Laboratory, “Timber demand is projected to recover from recession levels over time with the recovery of the housing market and the general economy. Previous higher levels of timber demand have been well within the productive capacity of U.S. forests. Increases in demand for softwood lumber will increase revenue to forest landowners and increase the likelihood that land will be retained as forest and increase the likelihood of conversion of some non-forest or natural forest to plantation.”

5

POTENTIAL CONTRIBUTION OF CLT TO GREEN BUILDING OBJECTIVES

In green building programs, there are currently limited incentives that would directly encourage the use of CLT on environmental merits. Some direct and indirect green building motivations relevant to CLT might include:

- **Renewable materials:** as a wood material, CLT is renewable. Forest practices in North America are typically aligned with sustainable forest management principles, ensuring that wood is renewed. CLT consumption will not overly burden the sustainable supply capacity of North American forests as demonstrated in the previous section.
- **Local materials:** CLT is manufactured in North America and potentially can be sourced within a radius deemed “local,” depending on the definition of local, location of final installation, and the possible future emergence of more manufacturers than the two currently in operation at the time of this writing (both are located in Canada).
- **Certified wood:** CLT manufacturers can obtain chain-of-custody certification for sustainable forestry management.
- **Carbon storage:** if incentives should emerge for the value of the carbon stored for decades in buildings, CLT might have a market advantage over other structural systems.
- **Carbon offsets:** if incentives should emerge for the value of the greenhouse gas emissions avoided when using CLT in place of other materials with a higher greenhouse gas footprint (in other words, a carbon offset), CLT may experience market advantage.
- **LCA used during building design:** a number of design guidelines for green design such as the California Green Building Standards Code, the International Green Construction Code, Green Globes® and LEED¹⁰ contain possible motivators for designers to use life cycle assessment during the design process with the goal that they produce buildings having minimal LCA impact. Previous literature suggests that CLT systems have lower LCA impacts than alternative systems (see literature review in Appendix A).
- **EPD credits:** at the time of this writing, the draft of LEED v.4, anticipated for release in summer 2013, includes a Materials and Resources credit for designers to select products that have published environmental product declarations (EPDs) or have a published manufacturer-specific cradle-to-gate LCA study. In addition, at the time of this writing, LEED has a pilot credit for EPDs and manufacturer-specific LCAs. At this time, the two North American manufacturers of CLT (Structurlam and Nordic) have LCA reports and are developing EPDs.

¹⁰ LEED Pilot Credit 63 (in place as of this writing; future status unknown given the pending arrival of LEED v.4) provides an incentive for designers to use whole-building LCA to show improvement of a final design over a reference building. This credit, in a slightly different form, is a new credit proposed for LEED v.4 (the 5th comment period version).

- **Health, comfort and well-being benefits:** Occupants exposed to wood have shown benefits in their well-being [Fell, 2010]; CLT—if left exposed—may contribute to a health and comfort objective. CLT does not adversely affect indoor air quality, as shown in the previous section.
- **Reusability:** As a panelized system, CLT has good potential for disassembly and reuse. Realizing this potential will require development of construction details for disassembly and the infrastructure to transfer products to a new site.
- **Operating energy savings:** CLT is a massive material with some thermal mass; thermal mass is often identified as a contributor to overall savings in a building’s heating and cooling loads and/or costs due to peak load shifting.
- **Efficient use of resources:** As a prefabricated product, CLT has minimal construction site waste, and construction time is shortened. Waste created at the time of manufacture is minimized by automation and can be fed back into the manufacturing plant’s biofuel plant for use as carbon neutral energy.

Material efficiency is an important sustainable design objective that requires discussion with respect to CLT. CLT buildings are massive, which is an unusual use of wood from the North American light-frame perspective. At first glance, CLT may appear wasteful, if we are comparing CLT to light-frame wood.

However, the distinction between light-frame and “heavy” construction is important in the assessment of efficiency and a key element in determining the environmental benefits of CLT. For example, when light gauge metal is compared with heavy steel braced frames, the question of material efficiency probably doesn’t arise. This is because most architects and engineers understand that there is a difference in application and required performance for each of these structural systems.

The intent of CLT is not to replace light-frame construction, but rather to offer a low-carbon alternative to “heavy” construction materials such as concrete and steel. There are building applications where light-frame construction is less appropriate, such as an industrial warehouse with 40’ walls that need to withstand the impacts of heavy machinery, or a Class A office building where few partition walls and minimal floor vibrations are desired. Traditionally, designers have relied on heavy construction materials such as concrete tilt up, steel frames and composite decking systems to achieve a solid structure with large spans and tall plate heights. Today, more designers are considering the use of a timber alternative.

When CLT is properly considered within the context of heavy construction systems, it can be an efficient use of wood. Nonetheless, every construction system should be designed for maximum efficiency, and there are methods for maximizing the effectiveness of CLT systems. For example:

- **Optimize span capabilities.** Whether it is tailoring a design to meet the maximum span of a specific CLT product or optimizing the layout to meet the demands of the design, designers and manufacturers should work together to maximize utilization of CLT’s structural capacity. Final CLT shop drawings and design are done by the manufacturer and each manufacturer will differ in their panel dimensions, lamination thicknesses, connections, wood species and preferred layout configurations. For this reason, it is important to engage the preferred fabricator early in the design process if some of these factors are critical for architectural or other requirements.
- **Optimize the openings.** When the panel layouts are established for a design, use beams over doorways and place windows in between full size panels to avoid waste that might be created if a full panel was used with cut out openings. Using more full sized panels also allows more versatility to reuse the panels later in the product lifecycle.

Both of these strategies may be initiated by CLT manufacturers in order to reduce costs. There are also more elaborate ways for designers to ensure efficient use of CLT:

- **Use folded diaphragms.** This is a sophisticated technique used with other heavy construction materials that enables CLT panels to span greater distances without increasing the wood fiber needed in the lamination. A folded plate design borrows stiffness from the out-of-plane diaphragm to increase the moment of inertia or stiffness of an assembly by increasing the effective distance between the extreme fibers in the bending plane. Connection design at the fold is critical but the load can be distributed along the entire joint instead of concentrated at discrete points.
- **Employ 3D structural analysis techniques.** CLT structures have the ability to act in three dimensions. Similar to a folded diaphragm, the cube effect takes advantage of CLT's ability to transfer load in all three axes in the same panel. A single CLT panel can take a vertical axis load anywhere in the plane of the panel, lateral shear load in the other axis of the same plane, and a bending load into the face of the panel and transfer the resulting shear in a third axis. Therefore, including a structural analysis that takes advantage of this cube effect may reduce the amount of material required in the overall structural design.
- **Account for disaster resilience capabilities.** In the world of sustainable design, the concept of disaster resilience is only going to become more prominent. There is a considerable advantage to having a building with the ability to quickly return to operation after a disaster and in the process minimizing the life cycle impacts associated with its repair. Based on the full scale seismic testing discussed in Chapter 4 entitled *Lateral design of cross-laminated timber buildings*, CLT structures may offer more disaster resilience than those built with other heavy construction materials. Because failures are designed to happen at the connections, the test building suffered isolated and minimal structural damage even after 14 consecutive shake table tests. Assuming the same results for an actual building, the rehabilitation and repair required following an earthquake would also be minimal.

6

MATERIAL DISCLOSURE

Cross-laminated timber contains only two materials: lumber and adhesive. For the two North American CLT manufacturers in commercial production at the time of this writing, lumber is locally sourced (maximum transportation distance 329 miles/530 km) and comprises a few softwood Canadian species. Two adhesives are used: polyurethane and arclin melamine.

7

CONCLUSIONS

In this Chapter, we assessed several attributes of CLT to determine if this product could be a contributor to green building objectives. Our conclusion is yes, CLT meets many criteria designers might be looking for when specifying materials for sustainable construction.

In particular, the use of wood in buildings prior to using the wood to produce energy offers clear advantages. As reported in numerous other studies¹¹, wood products typically contain more carbon than is emitted during harvest, manufacturing, transportation and end-use. This carbon was removed from the atmosphere when the living tree absorbed the greenhouse gas carbon dioxide. Based on our preliminary results, a significant portion of material-related greenhouse gas emissions from a CLT building in Québec are offset by the carbon storage benefits of wood and the potential for substituting fossil fuel energy sources with wood at the end of the building life.

From an environmental standpoint, carbon storage benefits involve a delayed greenhouse gas emission during the time that forests re-grow and re-sequester carbon; the carbon storage in wood products is temporary as the carbon will eventually return to the atmosphere, and, therefore, over a long time frame, has no effect on global carbon balances. However, a carbon-balance does not equal climate-neutral and delayed emissions from the storage of wood products provide quantifiable benefits for avoiding atmospheric warming over the short term (~100 years or so), as demonstrated by our results, that diminish over extended time horizons (Guest, Cherubini & Strømman, 2012).¹² Based on the urgent need to reduce greenhouse gas emissions in the short term to avoid “dangerous anthropogenic interference with the climate system” — internationally recognized as a global temperature change of more than 2°C (UNFCCC, 2010, p. 5) — the avoided GWP from using wood products in buildings presents an opportunity to contribute to short-term emissions reductions.

The carbon stored in wood products in long-term use such as construction is a substantial carbon pool which would be increased with the use of CLT. This product might help extend the timeline for this stored carbon, as CLT panels may be good candidates for recovery at the end of building life, for reuse in another building.

¹¹ For example, see the 40 papers reviewed in Werner, F. and Richter, K., 2007, *Wooden building products in comparative LCA: A literature review*; *International Journal of Life Cycle Assessment*, 12(7): 470-479; and the 66 papers reviewed in Sathre, R and O'Connor, J., 2010, *A Synthesis of Research on Wood Products and Greenhouse Gas Impacts*, 2nd Edition, FPInnovations.

¹² For a 100 year rotation period, Guest et al. (2012) show that 1 kg of wood products stored for 60 years has a GWP using a 100 year time frame of around -0.07 kg CO₂ eq, when incinerated at year 60, vs. a GWP using a 500 year time frame of -0.01 kg CO₂ eq.

8

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APPENDIX A

LITERATURE REVIEW

A1 Literature Review on Environmental Performance of CLT

There is very little existing LCA data or validated comparative studies addressing CLT. Several promotional pieces on the mid-rise Stadthaus building in England make comparative assertions about CLT, but these lack support literature, clarity and methodological accuracy.

Gustavsson et al. (2010) performed a full life cycle assessment of energy use and greenhouse gas emissions for a CLT mid-rise building in Sweden (part of the Limnologen project). Energy use and carbon flows are tracked along the entire chain and include carbon stocks in building products and avoided fossil fuel combustion emissions where biofuel residues are used as a substitute energy source for fossil fuel. The authors argue that a major carbon benefit for this wood-intensive building is the side effect of using wood residues as an energy substitute for fossil fuel. The biofuel can be collected in the form of harvesting residues, wood manufacturing residues, and—eventually—the CLT panels themselves at the end of their useful life.

Robertson (2010, 2012) conducted a comparative LCA study on a five-story office building made of concrete versus a CLT and glulam hybrid building, using a life cycle inventory from primary data gathered at a CLT pilot plant in British Columbia. Results indicate a lower environmental impact for the glulam/CLT building over the concrete building in nine out of eleven environmental indicators.

A mid-rise LCA study by John et al. (2009) could provide a comparative basis for examining the CLT results in the Swedish study. This New Zealand study performed full LCA for four different structural approaches to a six-story office building (concrete, steel, and two different wood versions). While results from the New Zealand study are not directly comparable to those of the Swedish study, we can potentially draw general conclusions about the likely comparative results for CLT. It is useful to look at the two versions of wood buildings in the New Zealand study. One used a fairly conventional quantity of structural wood while the other (called “timber plus” by the authors) increased the use of wood in that model by assuming wood substitution for additional products such as windows, ceilings and exterior cladding. The study found that total life cycle energy consumption and carbon footprint both decrease as the use of wood increases. A similar examination was performed by Meil et al. (2006) with similar results. In both studies, the reason for this benefit is the substitution of wood for non-wood materials that have a heavier energy/greenhouse gas footprint.

In the New Zealand study, various end-of-life scenarios were examined and operating energy was included; these are two important factors to consider when properly comparing wood to other materials in construction. In this study, thermal mass in the buildings was accounted for in the energy modeling, and the concrete building had the lowest operating energy consumption. However, this was overtaken by the embodied energy savings of the “timber plus” version over the concrete version due to product substitution. For the end-of-life landfilling scenario, the authors also contend that a significant portion of the carbon contained in the wood materials is stored permanently, giving both wood versions of the building lower total life cycle carbon footprints than the steel and concrete versions. The “timber plus” version has a substantially lower total carbon footprint than the other wood version due to embodied energy savings in product substitution, lower operating energy consumption due to thermal mass, and a greater mass of wood carbon in permanent landfill storage.

From this study, we can perhaps form a hypothesis about likely comparative performance of CLT. If we assume that CLT has a smaller manufacturing carbon footprint than concrete and that all other life cycle factors are similar to the “timber plus” model, it would follow that a CLT version would perform similarly or perhaps better than the “timber plus” model, given that it would have more wood mass available for permanent landfill storage at end of life.

In the Canadian edition of the CLT Handbook, a hypothetical LCA comparison was conducted (Mahalle et al., 2011). Glulam was used as a proxy for CLT, as no LCA data was available at that time. CLT was compared to concrete functional equivalents in the context of a mid-rise building and in the context of a floor. In both cases, the CLT option showed lower results in all impact measures and resource consumptions addressed in the study.

APPENDIX B

DETAILS ON THE MID-RISE LCA STUDY

B1 Objective and Method

The objective of the work reported here is to provide preliminary findings from an environmental life cycle assessment (LCA) of a 43,700 square foot, four-story (plus one underground level) CLT apartment building.

LCA is a ISO 14040/14044 (2006; 2006) standardized tool used to evaluate the environmental performance of a product, service or system.¹³ It involves evaluating the energy and material inputs, as well as wastes that are produced, throughout the supply chain and end-of-life disposal of a product. LCA is useful for identifying environmental hot-spots along the supply chain, for avoiding problem shifting where one environmental problem is 'solved' by shifting the environmental burdens in time or space from one phase of a product lifecycle to another phase, and for highlighting trade-offs between different environmental indicators.

Engineering and architectural drawings for an existing four-story CLT apartment building in Chibougamau, Québec, are used to create a detailed bottom-up material inventory for this assessment. The building lifetime is assumed to be 60 years. The Athena Impact Estimator is the building LCA tool adopted for this analysis. The Impact Estimator uses regional information in its calculations; Québec City was chosen as a location because it is the Impact Estimator predefined location closest to Chibougamau where the actual building is located.

As the results from this study are intended for use in a comparative building assessment to be released by FPIInnovations in 2013, building elements that were known or assumed to be identical were excluded. Those include: fenestration, exterior cladding, flooring, HVAC, hand railings, plumbing and electrical equipment, etc.

The system boundary describes the phases of the building lifecycle included in the analysis. These are: resource extraction and material production, construction, maintenance and replacement, demolition, and associated transport processes (see Figure 5). Building operation was assumed to be equivalent and excluded from the analysis. Further exclusions due to a lack of data included architectural and engineering services, and worker transport.

¹³ The terms product, system and service are used interchangeably throughout the rest of this Chapter and simply refer to the object of the LCA investigation.

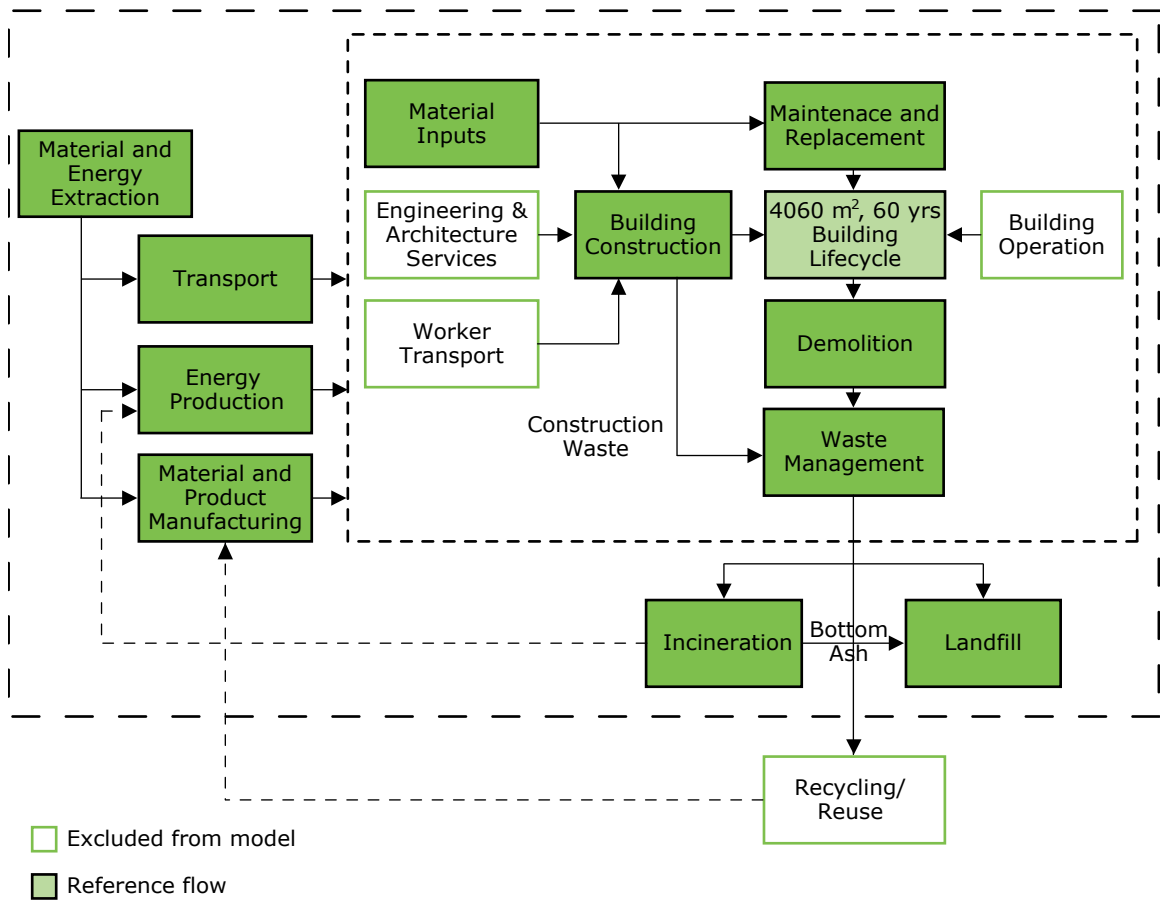


Figure 5
System boundary

Data collection for LCA involves developing a life cycle inventory (LCI) for all material, energy and service inputs and outputs of the system. When describing data requirements for a LCA, it is useful to distinguish between the foreground system, what is explicitly modeled, and the background system, which relies on secondary data sources.

The foreground system for this particular system was developed through detailed, bottom-up material estimates for a residential CLT building. An overview of the LCI developed for the foreground system is presented below.

The main sources for background data are embedded in the Athena Impact Estimator (v4.2.0130 (Athena Sustainable Materials Institute, n.d.)). The Impact Estimator includes the Athena Institute's regional, North American LCI database for building products, as well as energy and transport LCI data from the USLCI database. Additionally, the Impact Estimator includes estimates for transportation requirements, construction waste coefficients, construction effects, maintenance and replacement activities, and end-of-life treatment. A final important source of background data included cradle-to-grate LCI data for the manufacture of CLT in Chibougamau, Québec, over 310 miles (500 km) north of Québec City (Athena Sustainable Materials Institute, 2012b).

The impact assessment methodology and impact categories adopted for this assessment are a subset of the U.S. EPA's Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI) 2.0 (Bare, 2011), which is used by the Impact Estimator. The TRACI impact categories include:

- Global Warming Potential (GWP, measured in kg of CO₂ equivalent)
- Acidification Potential (AP, measured in moles of hydrogen ion (H⁺) equivalents)
- Respiratory Effects (RE, measured in kg of particulate matter (PM) up to 10 microns)
- Eutrophication Potential (EP, measured in kg nitrogen (N) equivalent)
- Ozone Depletion Potential (OD, measured in kg chlorofluorocarbon-11 (CFC-11) equivalent)
- Smog Potential (measured in kg of ozone (O₃) equivalent)

The Impact Estimator excludes TRACI impacts for human toxicity and ecotoxicity, which are listed as optional measures in ISO 21930 (2007) due to greater uncertainty in these measures. Fossil fuel consumption is also an indicator category used by the Impact Estimator which refers to non-renewable fossil fuel consumption plus feedstock fossil fuel and includes direct and indirect energy use along the supply chain.

CLT results from the Athena Sustainable Materials Institute (ASMI, 2012b) were developed in Simapro v7.3.3 using the TRACI 2.0, v4.00, methodology in addition to the Cumulative Energy Demand (CED) v1.06 method which was used for estimating total fossil fuel use in megajoules (MJ) for the production and delivery of CLT to the construction site.

B1.1 Life Cycle Inventory

Material quantities for the existing CLT building were estimated from structural engineering and architectural drawings for a recently completed CLT building in Chibougamau, Québec.

Construction effects in the Impact Estimator modeling include transport to the building site, construction waste factors, and the use of a diesel powered crane. Transport for the CLT panels, which are currently not contained within the Impact Estimator, were modeled using the USLCI process for diesel powered combination trucks and an estimated transport distance of 320 miles (515 km) from the CLT producer in Chibougamau to the building site in Québec City. Additionally, equivalent weight glulam data was used as a proxy in the Impact Estimator to estimate diesel consumption from crane operation during construction. Construction waste for CLT was assumed to be 0% since off-cuts, and cuts for doors and windows are accounted for upstream at the CLT manufacturing plant.

Maintenance and replacement is modeled using replacement schedules in the Impact Estimator. The exclusion of equivalent materials and building products, however, is such that most items requiring maintenance and replacement have been excluded from this study including paint, windows and doors, and finished flooring.

End-of-life effects in the Impact Estimator include demolition energy per unit of structural material and transport to the landfill. Transport to the landfill in the Impact Estimator is based on the percentage of materials that end up at the landfill, and an average, location specific, landfill distance. Impact Estimator assumptions for transport distances and material fractions ending up in disposal are hidden from the user. This study uses end-of-life transport assumptions from the Impact Estimator and applies these assumptions in Table 1 for modeling additional end-of-life processes. Those additional processes including incineration, landfilling and recycling are modeled using Simapro v7.3.3. Transportation of recycled materials from the building site is not included as these impacts are considered to belong to the next product lifecycle. Glulam results from the Impact Estimator were again used as a proxy of end-of-life results for CLT.

End-of-life impacts from wood products were assessed via scenario analysis of 1) landfilling, 2) municipal waste incineration and wood combustion in an industrial boiler and 3) avoided natural gas use due to the embodied energy content of the wood. Landfilling and incineration were assessed using ecoinvent v 2.2 waste treatment processes adjusted for a Québec electricity mix.

Wood combustion in an industrial boiler was modeled using the Franklin and Associates process for ‘Wood into Industrial Boiler FAL’ in Simapro v7.3.3. The wood moisture content for the Franklin and Associates process for ‘Wood into Industrial Boilers’ is not provided in the process documentation. The inventory of the process indicates that 1,000 lb. (454 kg) of wood is consumed to produce 1,050 lb. (476 kg) of biogenic CO₂. Assuming 50% of the mass of oven dry wood is carbon, this suggests an oven dry mass input of roughly 572 lb. (260 kg) of wood using a molar ratio of 12/44 for C/CO₂. In order to maintain the carbon balance, the stack emissions from wood combustion were estimated based on 1,000 lb. (454 kg) of wood into the process ‘Wood into Industrial Boiler FAL’ for every 572 lb. (260 kg) of oven dry wood waste. This assumes that the combustion emissions for a unit of wood are independent of the moisture content for that unit of wood. For the 1,143,073 lb. (518,489 kg) of oven dry wood in the CLT building, the emissions profile from 1,995,840 lb. (905,297 kg) of wood combustion from the Franklin and Associates process for ‘Wood into Industrial Boilers’ was inventoried.

The major particulate matter emission from the Franklin & Associates process for ‘Wood into Industrial Boiler’ was particulate matter (PM) <10 microns. Through the results, it was discovered that the TRACI 2.0 methodology has no respiratory effect emissions factor for these emissions. To address this deficiency, an average of the PM<10 emission factors from IMPACT 2002+ and RECIPE impact assessment methodologies available in Simapro V7.3.3 were used after re-scaling them to be consistent with TRACI 2.0 characterization factors.

Landfill gas capture is not included in the model for landfilling so the wood carbon is released as carbon dioxide and methane. A further adjustment for landfill modeling was to increase the assumed wood carbon released to the atmosphere for landfilled wood products, which is assumed in ecoinvent v2.2 (Doka, 2009) to be 1.5% following Micales & Skog (1997), to 23% following Skog (2008) with half of the wood decaying over 29 years. A proportion of 45% of landfilled carbon is assumed to be released as methane, while 55% are released as CO₂. These figures are representative of an anaerobic, managed landfill as defined by the IPCC (2006).

The energy content of wood—based on the lower heating value of red spruce with a wet basis moisture content of 20% (16.24 MJ/kg) and a boiler efficiency of 75% (Kostuik & Pfaff, 1997)—was assumed to avoid an equivalent amount of energy produced from natural gas consumed in an industrial boiler with a thermal efficiency of 80%.

The potential avoided emissions due to end-of-life metal recycling were excluded due to limitations with the Impact Estimator data. However, LCI data already includes benefits due to recycled products (e.g., rebar is made of mainly recycled steel) on the production side. To evaluate the potential benefits of reusing CLT panels, one scenario was developed to consider a second generation CLT building constructed with 50% reused CLT panels which were transported 31 miles (50 km) from a local storage facility.

Table 1

Material disposal assumptions

Materials	Landfilling	Incineration ¹	
	Reuse/Recycling %	Reuse/Recycling %	Incineration %
CLT	0	0	100
Kiln dried lumber	0	0	100
Plywood	0	0	100
PSL	0	0	100
Fiberboard	0	0	100
Gypsum board	15	15	0
Gypsum fiberboard	15	15	0
Steel	90	90	0
Galvanized steel	90	90	0
Concrete 20 MPa	100	100	0
Concrete 30 MPa	100	100	0
Mineral wool	50	50	0
Extruded polystyrene type IV	50	0	50
Expanded polystyrene type II	50	0	50
Polyisocyanurate (JME 3)	50	0	50
Polyurethane insulation	50	0	50

¹Materials not reused/recycled or incinerated are landfilled

Finally, the net GWP due to biogenic carbon is estimated as the difference in GWP due to carbon sequestration from forest growth and the GWP due to biogenic carbon emissions over a 100 year period (Bright, Cherubini, & Strømman, 2012; Cherubini, Peters, Berntsen, Strømman, & Hertwich, 2011a; Guest, Cherubini, & Strømman, 2012; Levasseur, Lesage, Margni, Deschênes, & Samson, 2010). The Schnute model (Cherubini, Strømman, & Hertwich, 2011b referencing Schnute, 1981) was used to model forest regrowth. The model was parameterized using data from Bright et al. (2012) based on a harvest cycle of 90 years for a boreal forest in Eastern Canada (Athena Sustainable Materials Institute, 2009). The end of the 90 year growth cycle was normalized to the total quantity of wood in the CLT building. Numerical approximation was used to compute the results using a 1 year time-step.

B2 Results

Absolute values for the results presented in the report can be found in Table 2.

Table 2
Absolute values for total life cycle impacts

		Manufacturing	Construction	Maintenance	EOL	EOL - no long-term emissions	Net Biogenic GWP	Additional Forest Sequestration due to CLT Reuse	Fossil Fuel Substitution
Fossil Fuel Consumption (MJ)	CLT, LF	3.2E+06	6.7E+05	0.0E+00	5.6E+05	5.58E+05	0.0E+00	0.0E+00	0.0E+00
	CLT, LF, 50% Reuse	2.5E+06	5.1E+05	0.0E+00	3.5E+05	3.54E+05	0.0E+00	0.0E+00	0.0E+00
	CLT, INC	3.2E+06	6.7E+05	0.0E+00	3.7E+05	3.74E+05	0.0E+00	0.0E+00	-1.1E+07
Global Warming Potential (kg CO ₂ eq)	CLT, LF	2.0E+05	4.5E+04	0.0E+00	3.3E+04	3.26E+04	-1.3E+05	0.0E+00	0.0E+00
	CLT, LF, 50% Reuse	1.6E+05	3.3E+04	0.0E+00	2.1E+04	2.09E+04	-7.2E+04	-7.7E+04	0.0E+00
	CLT, INC	2.0E+05	4.5E+04	0.0E+00	4.9E+04	4.91E+04	-1.1E+05	0.0E+00	-2.5E+05
Acidification Potential (moles of H ⁺ eq)	CLT, LF	8.4E+04	1.4E+04	0.0E+00	5.8E+03	5.76E+03	0.0E+00	0.0E+00	0.0E+00
	CLT, LF, 50% Reuse	6.3E+04	9.8E+03	0.0E+00	3.8E+03	3.77E+03	0.0E+00	0.0E+00	0.0E+00
	CLT, INC	8.4E+04	1.4E+04	0.0E+00	3.0E+04	3.05E+04	0.0E+00	0.0E+00	-7.0E+04
Respiratory Effects (kg PM ₁₀ eq)	CLT, LF	6.3E+02	2.1E+01	0.0E+00	3.1E+01	3.08E+01	0.0E+00	0.0E+00	0.0E+00
	CLT, LF, 50% Reuse	5.8E+02	1.7E+01	0.0E+00	1.9E+01	1.89E+01	0.0E+00	0.0E+00	0.0E+00
	CLT, INC	6.3E+02	2.1E+01	0.0E+00	1.6E+02	1.58E+02	0.0E+00	0.0E+00	-1.1E+02
Eutrophication Potential (kg N eq)	CLT, LF	8.0E+01	1.4E+01	0.0E+00	4.7E+03	4.00E+01	0.0E+00	0.0E+00	0.0E+00
	CLT, LF, 50% Reuse	6.5E+01	1.0E+01	0.0E+00	2.6E+03	2.27E+01	0.0E+00	0.0E+00	0.0E+00
	CLT, INC	8.0E+01	1.4E+01	0.0E+00	5.2E+01	5.20E+01	0.0E+00	0.0E+00	-8.7E+01
Ozone Depletion Potential (kg CFC-11 eq)	CLT, LF	8.1E-04	1.8E-06	0.0E+00	3.2E-03	3.18E-03	0.0E+00	0.0E+00	0.0E+00
	CLT, LF, 50% Reuse	5.7E-04	1.3E-06	0.0E+00	1.9E-03	1.89E-03	0.0E+00	0.0E+00	0.0E+00
	CLT, INC	8.1E-04	1.8E-06	0.0E+00	5.4E-04	5.37E-04	0.0E+00	0.0E+00	-3.3E-04
Smog Potential (kg O ₃ eq)	CLT, LF	1.8E+04	6.9E+03	0.0E+00	2.5E+03	2.51E+03	0.0E+00	0.0E+00	0.0E+00
	CLT, LF, 50% Reuse	1.2E+04	5.0E+03	0.0E+00	1.7E+03	1.67E+03	0.0E+00	0.0E+00	0.0E+00
	CLT, INC	1.8E+04	6.9E+03	0.0E+00	1.9E+04	1.86E+04	0.0E+00	0.0E+00	-4.3E+04

B2.1 Assumptions and Limitations

There are a few limitations to note with respect to these preliminary results which are discussed briefly in this section.

A minor issue in the current model includes missing elements in the life cycle inventory beyond the intended exclusions listed previously. These include balconies, stairs, and hardware connections. While these will be incorporated in the comparative building LCA produced by FPInnovations in 2013, their impact on the overall result is expected to be minor given the scale of these materials compared to the overall building. While material requirements for connections of wood columns and beams were estimated using the column and beam assembly tool in the Impact Estimator, hardware for other assemblies including CLT walls and floors are currently excluded from the CLT building.

For many products, manufacturer specific LCI data was not immediately available. While many types of mineral wool were used in the CLT building, for example, they were all inventoried in the Impact Estimator using the generic mineral wool product in the Impact Estimator database. Due to extensive data requirements in LCA, such practices are common for modeling large systems and allow for order of magnitude considerations for different materials. For designers, product specific data is more useful when choosing between functionally equivalent products.

For products such as concrete and steel where the type and quantity can have an important influence on impact categories such as fossil energy consumption and climate change, it is important to be as precise as possible when inventorying materials. Unfortunately, the Impact Estimator only has 2,900, 4,350 and 8,700 pounds per square inch (psi) concrete as inventory items whereas 3,625 and 5,075 psi concrete was indicated in the structural engineering documents for various footing, and column elements. As a conservative assumption, concrete strength was rounded down to the nearest strength grade present in the AIE which implies a lower quantity of greenhouse gas-intensive cementitious material. All concrete was assumed to have average fly ash content.

Due to the high demolition energy required for glulam, future work should investigate the legitimacy of assuming that glulam can act as a proxy for CLT. The important question is whether or not the massive quantity of CLT can be reused or whether it will be chipped into small pieces similar to glulam beams.

The current work assumes the forest products are harvested from sustainably managed forests, since the Québec CLT producer uses wood certified by the Forest Stewardship Council, such that the net change to forest biomass is constant over the building life cycle. Land-use changes represent an important contributor to greenhouse gas emissions. If the harvesting rate were to exceed the annual growth rate of the forest, or the harvested forest area is used for agriculture or urbanization, the loss in forest stock would represent a net source/sink of carbon that would be important to allocate to forestry activities. As previously elaborated in Section 4, however, the growth rate of U.S. forests continues to outpace the removal rate.

The model for forest re-growth in this analysis takes place at the level of the individual stand of trees required to replace the quantity of wood stored in the building. Analysis at this level has been criticized for lacking perspective of the dynamics that occur at the landscape level where biomass stocks can be constant or increasing while harvesting takes place (Malmshheimer et al., 2011). On the one hand, the view expressed by Malmshheimer et al. fails to consider changes in the total landscape carbon stock due to continued forest operations. Presumably the entire forest stock of the United States would be able to sequester more carbon if left un-harvested up to a point where forest mortality from natural causes is equal to the growth rate. On the other hand, stand level analysis such as that undertaken in this assessment, do not consider risks from forest fire, pests and other natural events. Accounting for these events would increase the GWP benefit of using a wood product like CLT due to the potential for avoiding biogenic carbon emissions that would otherwise be released into the atmosphere from forests such as those devastated by the pine beetle in the Northwestern United States. However, as Malmshheimer et al. (2011) point out, “tracking down wood over long time intervals in an extensive forest inventory still is not feasible because no system of accounting for components of change, analogous to growth, removals, and mortality of standing trees, has been

developed” (p. S38). Given the present dilemma, analysis at the stand level provides a useful first approximation of the GWP benefits from using wood resources.

A final limitation of the current analysis is that changes in albedo of the land due to harvesting are also excluded from the model due to significant uncertainties in quantifying this parameter over the harvest cycle (Bright et al., 2012). Albedo is a measure of how reflective the surface of the earth is. The change in albedo due to glacial melting in the arctic, for example, is a significant concern for global warming because ice reflects significant amounts of solar radiation which provides a cooling effect on the planet. The exclusion of albedo changes is an important limitation as preliminary results suggest that changes in albedo due to forest harvesting in northern latitudes are potentially significant in the first decade after harvesting (Bright et al., 2012; O’Halloran et al., 2012).

B2.2 Sensitivity

This section qualitatively addresses the sensitivity of the results to key parameters. These parameters are related to fossil fuel substitution and the GWP from biogenic carbon.

Fossil Fuel Substitution

For estimating the potential benefits for substituting wood bioenergy for fossil fuels, natural gas was selected as the fossil fuel. While the quality of individual fuel sources varies, natural gas represents a relatively clean fossil fuel with comparatively low life cycle emissions compared to coal and oil. According to Franklin & Associates process in Simapro v7.3.3, Life cycle GHG emissions per unit energy are 18-49% lower per unit of energy for natural gas compared to coal, distillate fuel oil and residual fuel oil. Of the reported emissions in this study, only acidification emissions are higher for natural gas compared to coal and this is due emissions upstream from the combustion process. Compared to oil, respiratory effects, smog, and eutrophication emissions are comparable to residual fuel oil, and 35-40% higher than distillate fuel oil.

The Franklin and Associates (FAL) process was selected for being representative of North American data. Of note, smog emissions and acidification emissions are significantly higher for the FAL process for natural gas combustion in an industrial boiler compared to ecoinvent processes that have been adjusted to a North American electricity mix via the US-EI database (Earthshift, n.d.). At the same time, ozone depleting and eutrophic emissions were lower for the FAL process. However, it should be pointed out that the avoided emissions from these later categories did not register when the results were normalized to per capita, yearly U.S. emissions (refer back to Figure 2).

GWP of Biogenic Carbon

Several parameters affect the GWP of biogenic carbon, including the carbon storage period in the anthroposphere (i.e. building lifetime), the growth rate of trees, and forest management practices (Guest et al., 2012; Cherubini et al., 2011b).

Guest et al. (2012) demonstrate that longer storage periods lead to larger reductions in GWP from biogenic sources as the harvested land is capable of re-absorbing more of the CO₂ extracted for the building products. Quicker growing trees lead to a greater GWP benefit (reduction in GWP) while slower growing trees create less of a GWP benefit trees harvested after the same period of time (Cherubini et al., 2011a and b). Finally, economic pressure, for example, to harvest early in their growth cycle will lower the GWP benefits from using wood products while delayed harvesting will also provide greater GWP benefits (Cherubini et al., 2011a and b).

B3 Discussion

The results presented in this preliminary analysis demonstrate significant benefits from the carbon storage of wood products and the importance that end-of-life management has for overall results. The potential for using wood to produce heat and substituting for natural gas, for example, implies potentially making the CLT system described above—which has excluded various building elements for simplification—a net negative consumer of fossil fuels and a negative emitter of greenhouse gases and acidifying substances.

Comparisons with other studies need to be made with caution to consider the influence of differences in system boundaries, production technologies, energy supply, impact assessment methodologies and more. As discussed in the literature review, Robertson et al. (2012) is the only previous work known to us to consider lifecycle impacts of a CLT building. Their study compares the CLT building to a functionally equivalent alternative. Unfortunately the majority of their results are presented in terms of the relative difference between the two buildings rather than in absolutes, which would have facilitated our interpretation of and comparison with their findings.

B3.1 End-of-life Scenarios

As seen in the results section, end-of-life scenarios have the potential to significantly impact the overall results. When landfilled, for example, a large fraction of carbon continues to be sequestered in the wood while a smaller fraction decomposes over an extended time horizon leading to the release of CO₂ and methane (CH₄) which is 23 times more potent than CO₂ on a mass basis. Greenhouse gas emissions are often assessed over a 100 year time frame. If we assume a service life of 60 years, then wood in landfill slowly releases greenhouse gases starting at year 60. The incineration scenario, which captures the wood's embodied energy as heat in a waste to energy facility, on the other hand, releases all of the wood's stored carbon as CO₂ at year 60. Interestingly, however, the reduction in global warming potential of the CLT building due to carbon sequestration is similar over a 100 year time span for both the landfill scenario and the incineration scenario. While the landfill emissions occur more slowly, the methane release is a more powerful greenhouse gas such that at year 100, the avoided global warming potential due to carbon sequestration is almost the same for landfilling compared to incinerating the wood in a waste to energy facility.

Reusing CLT panels has the potential to further reduce emissions by 12-44%, depending on the impact category, and can further enhance the removal of carbon from the atmosphere by avoiding the harvest of wood from forests which can continue to mature and absorb carbon.

By incinerating the CLT and capturing its embodied energy in a waste to energy facility, it is also possible to avoid the use of fossil energy sources which can potentially lead to significant reductions in fossil fuel consumption, global warming potential, acidification, and smog formation.

B3.2 Carbon Storage

Wood is about half carbon, and wood in long-term service such as buildings represents a significant pool for carbon. Over the long term, this carbon will return to atmosphere and complete the natural carbon cycle; in other words, wood products are not a permanent GHG removal mechanism. But the temporary carbon storage in wood products can be reasonably taken as a carbon credit, depending on time frame and end-of-life assumptions. This reasoning largely stems from the current urgency around climate change, where any delay in carbon emission is helpful in “buying time” to find mitigation solutions to climate change. Over a longer time frame, issues regarding landfill decomposition and potential release of methane become important. If the wood is burned at end of life for energy recovery to replace fossil fuel, the avoided GHG emissions from fossil fuel are included in the assessment.

For traditional wood structural systems, the carbon mass of wood is relatively small compared to the carbon emissions avoided by using wood instead of steel or concrete. Therefore, an important focus in the use of wood to combat climate change is to increase our rate of wood substitution for other materials, with less emphasis on carbon storage. With CLT, the relationship is the opposite: the carbon mass of wood is quite large compared

to the avoided emissions of alternate materials. In this case, there would be an interest in putting a value on that stored carbon, with a motivation to keep the carbon in service for as long as possible, and to capture the energy value of that carbon to replace fossil fuel at the end of service life.

However, there are important considerations before simplistically taking a credit for the carbon stored in wood; these are discussed here briefly but are beyond the scope of this Chapter. The climatic significance of carbon storage in wood products partly depends on the dynamics of the products pool as a whole, i.e., whether the total quantity of stored carbon is increasing, decreasing or is stable. Atmospheric carbon concentration is affected by *changes in the size* of the wood product pool, rather than by the *size* of the pool itself. In the short to medium terms, significant climate benefits can result from increasing the total stock of carbon stored in wood products, by using more wood products or using longer-lived wood products. In the long term, as the stored carbon in the stock of products stabilizes at a higher level, wood products provide a stable pool of carbon as new wood entering the pool is balanced by old wood leaving the pool, with climate benefits accruing from the carbon re-sequestered through tree regrowth and the substitution effects of avoided emissions. As discussed in Sathre O'Connor (2010), some wood substitution studies have covered a relatively short time frame, and have considered carbon storage to be equivalent to avoided emissions, while other studies have considered the long term carbon dynamics of wood products, and show that the substitution effect of avoiding fossil emissions is ultimately much more significant than the carbon stored in wood products.

Guest, Cherubini, & Strømman, (2012), and Levasseur et al. (2012) point out that the benefits of carbon storage are typically unaccounted for in LCA studies as biogenic carbon emissions are treated as having no effect on the climate due to their origin in the biosphere. This simplifying assumption can lead to perverse outcomes when long lived products are being evaluated (Malmshemer et al., 2011). However, there is disagreement about exactly how the benefits from carbon storage should be modeled.

Guest et al. (2012) and Levasseur et al. (2012) both survey common approaches for estimating the benefits from carbon storage in LCA and suggest that a dynamic approach, accounting for the point in time when carbon emissions are sequestered and released, provides a more realistic picture of the benefits of carbon storage from long-lived wood products. These authors both consider the harvesting and regrowth of a particular stand of trees in their respective analysis. While such a narrow spatial focus on a particular stand of trees misses the important dynamics occurring at the landscape level, the lack of current models for comprehensively evaluating forest growth, removals and mortality have already been mentioned (Malmshemer et al., 2011).

Given the complications and lack of agreed upon methodology for modeling forest dynamics in life cycle assessments of wood products, the benefits from carbon sequestration in this study should be interpreted with caution and likely under report the actual benefits due to carbon storage in the anthroposphere. While the methodology used in this study provides a useful starting point for considering the GWP benefits from CLT use, important methodological work is needed to evaluate the effects from changes in albedo in addition to forest dynamics that operate at the landscape level.

APPENDIX C

DETAILS OF THE VOC TESTING

In this Section, we provide preliminary findings regarding emissions to indoor air from cross-laminated timber. This data applies to CLT made from Canadian species.

C1 Objectives and Background

As regulatory and non-governmental organizations (NGOs) address indoor air quality issues, they tend to focus on volatile organic compounds (VOCs), including formaldehyde, as key factors relating to the discomfort reported by people working or living inside “air tight” buildings. The World Health Organisation (WHO) has defined VOCs as organic compounds with boiling points between 122°F (50°C) and 500°F (260°C). Wood composite products are suspected of emitting some of these organic chemicals, namely formaldehyde, alpha- and beta-pinene, carene, camphene, limonene, aldehydes, ketones and acetic acid. Although VOC and formaldehyde emissions from unfinished and finished wood composite panels are well documented, very little if any data exist on multi-ply products (in other words, products with multiple wood layers like cross-laminated timber and plywood).

C2 Procedures and Results

All measures were done in general agreement with the specified standards and protocols. The precision levels were in accordance with the technical requirements.

C2.1 Materials Sampling, Packaging, Transportation and Conditioning

Duplicate test samples of 11 inches x 30 inches (280 mm x 760 mm) (Figure 6) were cut 12 inches (300 mm) from each end of an 18 feet (5.5 meters) long original CLT panel. In order to avoid any potential contamination of samples, latex gloves were worn during the whole sampling and packaging processes; also, before cutting the samples, a towel was used to clean the saw blade. Samples were wrapped with plastic foil with no writing on the sample or on the packaging and stacked in a conditioned room ($23\pm 1^\circ\text{C}$ and $50\pm 5\%$ RH) until ready for testing. All samples were tested within one month after production.

VOC and formaldehyde tests were performed from the same sample and at similar conditions, at a loading ratio of $0.44\text{ m}^2/\text{m}^3$ with all edges sealed with a non-emitting aluminum tape material leaving two flat surfaces exposed.



Figure 6

Picture showing a prepared sample with edges sealed ready to be put in the chamber

C2.2 **Method**

A constant and adjustable airflow, conditioned for relative humidity, was fed through small environmental chamber at a rate which corresponds to an air change rate of one per hour. The VOC sampling procedures excluding formaldehyde were similar to those described in the ASTM D5116-97 and ANSI/BIFMA M 7.1-2007 standards. The chamber was constructed in stainless steel and the interior surfaces were electropolished to minimize chemical adsorption. The chamber was equipped with suitable accessories such as inlet and outlet ports for airflow and an inlet port for temperature/humidity measurements. The air sampling was accomplished from the airflow outlet port. The small chamber was placed inside a controlled temperature room. The humidity of the air flowing through the chamber was controlled by adding deionized water to the air stream, as shown in Figure 7.



Figure 7

A general view of the 1 m³ environmental chamber used for emissions testing

The collection of VOCs on an appropriate adsorbent medium is required to avoid overloading of the analytical equipment. In order to maintain integrity of the airflow in the small chamber, the sampling flow rate was 100 ml/min for a sampling period of 120 minutes for VOC sampling, while the formaldehyde sampling rate was set at 1.5 L/min for 120 minutes for a total of 180 L.

Tenax cartridges were used to sample VOCs and derivatized DNPH cartridges were used to sample low molecular weight formaldehyde and acetaldehyde. Higher molecular weight aldehydes are sampled with tenax tubes used for sampling VOCs. VOC sample tubes were analyzed by desorbing the VOCs through a thermal desorption system and then injected into a gas chromatograph equipped with a mass detector (GC/MS). Aldehyde tubes were desorbed with acetonitrile solvent and injected into a high performance liquid chromatograph (HPLC). Table 3 describes the small chamber operating conditions, while Table 4 summarizes the GC/MS and the HPLC operating conditions.

Table 3

Small chamber operating conditions

Parameter	Symbol	Unit	Value
Chamber volume	V	m ³	1.0
Loading ratio	Lr	m ² /m ⁻³	0.44
Temperature	T	°C	23±1
Relative humidity	RH	%	50±5
Air exchange rate	ACH	h ⁻¹	1.0
Sampling time		Hours	24

Table 4

TDU/GC/MS and HPLC operating conditions

Thermal Desorption Unit (Type ACM 900)	
Desorption temperature	250°C
Desorption time	6 min
Cryofocus Unit Model 951	
Cooling temperature	-50°C
Time	4 min
Desorption temperature	150°C
Desorption time	15 min
GC/MS: Agilent 5890 Series II Plus	
Carrier gas	He, 43.2 cm/sec
Column J&W Scientific DB-1	30 m x 0.25 mm ID, 1.0 µm
Injection type	Split: 22:1 at 230°C
Oven heating program	10 min at 70°C
	8°C/min at 200°C
	3 min at 200°C
Detector	MSD, transfer line temp. 280°C
HPLC Type: Agilent Series 1100	
Column Zorbax Eclipse XDB-C18	Analytical 4.6 mm x 150 mm, 5 microns
Phase mobile	70% ACN:30% water
Flow rate	1.0 mL/min
Total injected volume	25 µL
Column temperature	20°C
Detector	DAD 360 nm

C2.3 Quantification of Formaldehyde

Formaldehyde emissions were quantified according to the modified National Institute of Occupational Safety and Health (NIOSH) Test Method 3500. The method can be summarized as follows: 4 mL of the scrubber's content and 0.1 mL of 1.0% chromotropic acid are poured in a 50 mL Pyrex® test tube with a screw top cap. Six mL of concentrated sulphuric acid (96%) are slowly added and agitated for 2 minutes, then heated for 30 minutes at 100°C and cooled and tested in triplicate. Solution absorbencies were read through a UV-visible spectrophotometer set at 580 nm. Distilled water was run as a blank, and with a formaldehyde solution calibration curve, absorbency readings are then converted into µg/mL of formaldehyde. When the condensate samples were too concentrated to yield absorbencies in the linear range of the calibration curve, aliquots of these samples were diluted with distilled water to a level within the linear range of the calibration curve. The concentration obtained from this dilution was back-calculated to the original concentration and presented as micrograms of formaldehyde per liter, which is then converted into parts per million (ppm) and in emission factors as mg/m³.h.

C2.4 Quantification of the TVOC

VOC measurements from panel samples were conducted in accordance with the ASTM D5116-97 guide and described in great detail in Barry et al. (1999). A Thermal Desorber/Gas Chromatograph/Mass Spectrometer (TDU/GC/MS) system was utilized to desorb and quantify the total volatile organic compounds (TVOC). A “cryo-trap” device was connected to the GC column in order to “cryofocus” the thermally desorbed chemicals prior to their injection into the GC. The GC oven was programmed for 10 minutes at 70°C, followed by ramping up the heat to 200°C at a rate of 8°C/min, and held for 10 minutes. The mass scan ranged from 29 to 550 atomic mass units (amu). Quantitative evaluation was achieved by comparing the chromatogram peak area of each compound to the corresponding peak area of a standard.

C3 Results and Discussions

Tables 5 and 6 summarize the emitted VOCs including formaldehyde, acetaldehyde and acetone expressed in micrograms per cubic meter (µg/m³). To better illustrate the variation of emissions as a function of the product types, the results are graphically shown in Figures 8 and 9; the same scale was applied to both figures for an easy comparison. As one can see from these figures, no correlation exists between emission results and the number of glue lines involved in each product category or product thicknesses. Also, most of the emitted VOCs, if we except formaldehyde and acetaldehyde, are those usually emitted from softwood species, indicating that only formaldehyde and acetaldehyde could really be associated with the products manufacturing processes. Figure 10 compares the total volatile organic compounds (TVOC), excluding formaldehyde, acetaldehyde and acetone, emitted from the five different products tested; as for individual VOCs, no correlation can be established between TVOCs, the thickness or the number of plies in cross-laminated lumber products.

Table 5

Samples 24-hour individual VOCs (iVOCs), TVOC as toluene, between n-C6 and n-C16 including formaldehyde ($\mu\text{g}/\text{m}^3$)

VOCs	CAS #	114-3S			95-3S		
		A	B	Mean	A	B	Mean
Acetic acid	64-19-7	N/A*	6.7	6.7	2.4	<2.0	2.4
Hexanal	66-25-1	5.0	9.4	7.2	2.9	4.3	3.6
Alpha-pinene	7785-70-8	134.7	218.1	176.4	44.7	26.2	35.4
Beta-pinene	18172-67-3	14.6	32.7	23.6	9.9	7.8	8.8
Alpha-phellandrene	99-83-2	4.7	N/A*	4.7	2.7	3.1	2.9
3-carene	13466-78-9	19.1	51.0	35.0	3.6	8.3	6.0
Para-cymene	99--87--6	78.6	5.9	42.3	43.0	45.4	44.2
Limonene	95327-98-3	7.6	11.7	9.6	3.3	2.8	3.0
Unknown	- - -	- - -	- - -	- - -	4.9	5.3	- - -
TVOC _{alpha-pinene}	- - -	264.3	335.5	299.9	117.3	103.2	110.2
Formaldehyde	50-00-0	16.6	21.5	19.1	9.6	8.7	9.1
Acetaldehyde	75-07-0	70.1	149.7	109.9	107.3	51.0	79.1
Acetone	67-64-1	33.2	65.3	49.2	45.7	24.4	35.0

* Compound which $\mu\text{g}/\text{m}^3$ concentration is below the quantification limit allowed by ANSI BIFMA.

Table 6

Samples 24-hour individual VOCs (iVOCs), TVOC as toluene, between n-C6 and n-C16 including formaldehyde ($\mu\text{g}/\text{m}^3$)

VOCs	CAS #	190-5S			152-5S			210-7S		
		A	B	Mean	A	B	Mean	A	B	Mean
Acetic acid	64-19-7	3.8	3.9	3.9	2.8	<2.0	2.8	2.8	2.1	2.4
Hexanal	66-25-1	4.4	3.8	4.1	3.1	2.6	2.8	4.4	2.1	3.2
Alpha-pinene	7785-70-8	67.9	143.5	105.7	98.6	20.5	59.6	64.9	35.2	50.0
Beta-pinene	18172-67-3	14.0	8.5	11.3	7.3	4.5	5.9	7.9	6.7	7.3
Alpha-phellandrene	99-83-2	2.7	<2.0	2.7	<2.0	2.3	2.3	<2.0	<2.0	<2.0
3-carene	13466-78-9	9.3	9.6	9.5	36.2	5.9	21.1	8.3	5.5	6.9
Para-cymene	99--87--6	36.4	<2.0	36.4	2.8	32.5	17.7	3.0	13.6	8.3
Limonene	95327-98-3	10.7	4.6	7.7	3.4	2.3	2.8	4.2	2.7	3.5
Unknown	---	---	---	---	---	2.4	---	---	---	---
TVOC _{alpha-pinene}	---	149.2	174.1	161.7	154.3	72.9	113.6	95.4	68.0	81.7
Formaldehyde	50-00-0	9.4	8.8	9.1	5.7	6.5	6.1	6.0	5.4	5.7
Acetaldehyde	75-07-0	71.5	68.5	70.0	72.6	74.4	73.5	73.6	59.4	66.5
Acetone	67-64-1	22.3	27.6	24.9	31.2	29.8	30.5	21.5	16.1	18.8

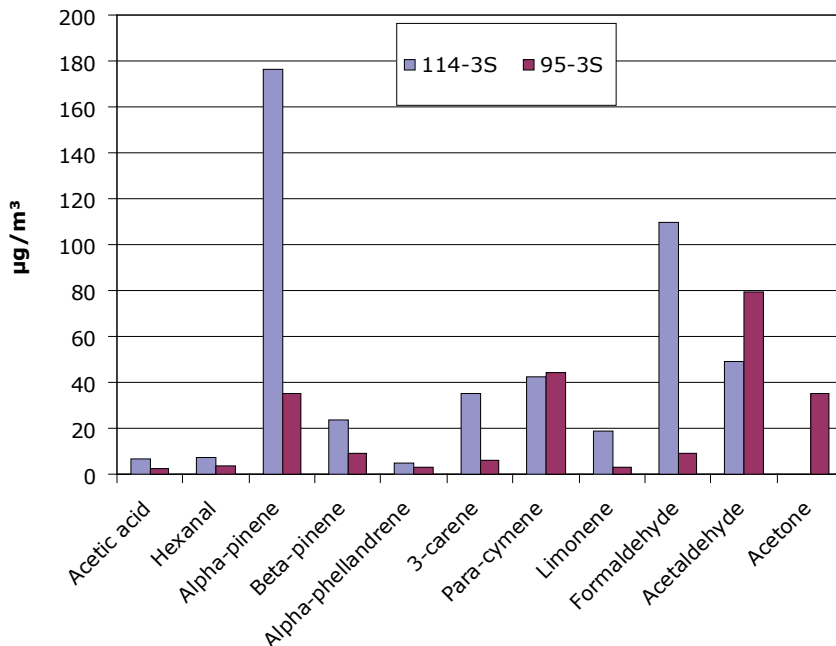


Figure 8

24-hour VOCs including formaldehyde and acetaldehyde off gassing as a function of samples types

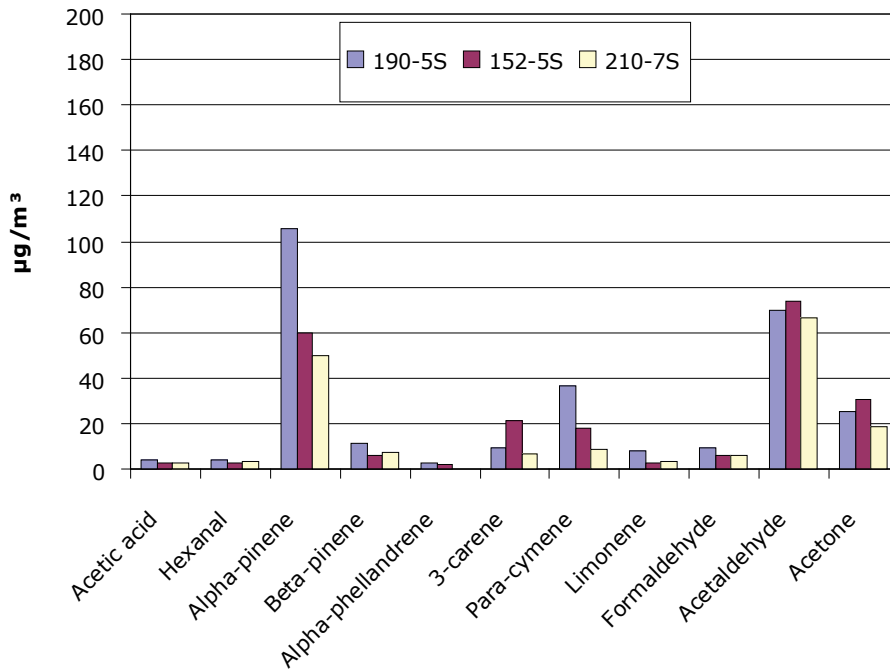


Figure 9
24-hour VOCs including formaldehyde and acetaldehyde off gassing as a function of samples types

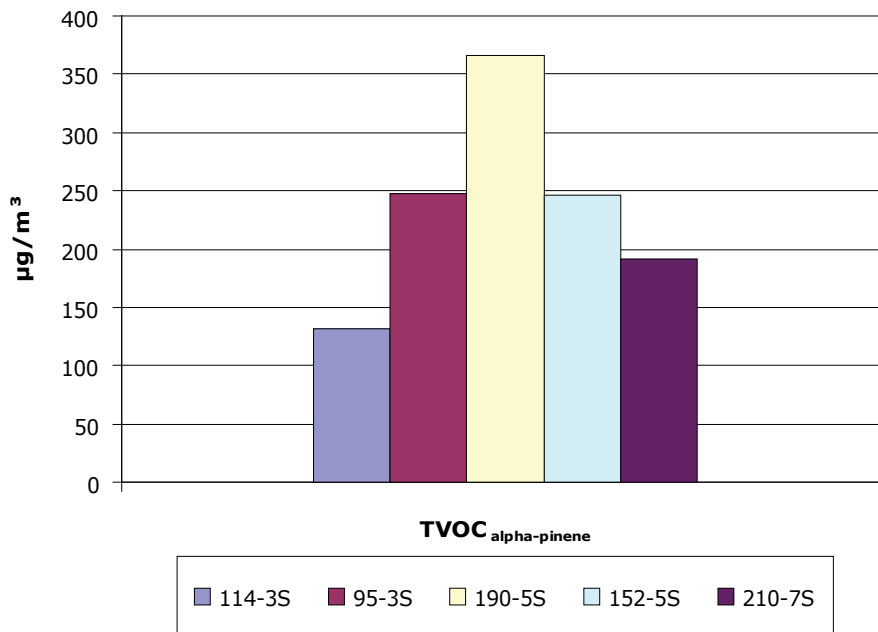


Figure 10
24-hour TVOC emissions as a function of cross-laminated products

Examples of emission labeling systems in Europe in terms of VOCs, including formaldehyde and acetaldehyde, are summarized in Table 7 in order to put the tested cross-laminated timber products emissions in context and to allow manufacturers interested in labeling their products for overseas market. Because few individual VOC emission limits are expressed in emission factors (EF), i.e., mass of the emitted VOC per square meter of the product tested per hour ($\mu\text{g}/\text{m}^2\cdot\text{h}$), the cross-laminated timber products emissions results have been converted into emission rates and summarized in Table 8 and Table 9. Results of emission factors reported in Tables 8 and 9 were calculated from the 24-hour sampling time compared to the voluntary limits listed in Table 7 calculated after 3, 10 or 28 days of samples exposure in the environmental chamber. One should expect that the cross-laminated timber emission factors would be much lower if their exposure is prolonged for an additional 3, 10 or 28 days and meet the most stringent Blue Angel or GUT (Germany) TVOC emission limits not met after 24 hours of exposure.

To convert measured individual VOC emissions or total VOC, both expressed in $\mu\text{g}/\text{m}^3$, in the environmental chamber into emission factors, knowing the flow rate $Q(\text{m}^3/\text{h})$ and the total exposed surface area of the sample $A(\text{m}^2)$, one can use the following equation:

$$\text{EF} (\mu\text{g}/\text{m}^2\cdot\text{h}) = C(\mu\text{g}/\text{m}^3) * Q(\text{m}^3/\text{h})/A(\text{m}^2)$$

Table 7

Example of some European emission labeling systems

Label	Origin	TVOC	Aldehydes Additional Requirements
AgBB	Germany	10 mg/m^3 (3 days) 1 mg/m^3 (28 days)	DIBt: 120 $\mu\text{g}/\text{m}^3$ (28 days)
CESAT	France	5000 $\mu\text{g}/\text{m}^3$ (3 days) 200 $\mu\text{g}/\text{m}^3$ (28 days)	Formaldehyde: 10 $\mu\text{g}/\text{m}^3$ (28 days)
M1	Finland	200 $\mu\text{g}/\text{m}^3$ (28 days)	Formaldehyde: 50 $\mu\text{g}/\text{m}^3$ (28 days)
LAQI Scheme	Portugal	5000 $\mu\text{g}/\text{m}^2\cdot\text{h}$ (3 days) 200 $\mu\text{g}/\text{m}^2\cdot\text{h}$ (28 days)	Formaldehyde: 10 $\mu\text{g}/\text{m}^3$ (28 days)
Natureplus	Germany	5000 $\mu\text{g}/\text{m}^2\cdot\text{h}$ (3 days) 200 $\mu\text{g}/\text{m}^2\cdot\text{h}$ (28 days)	Formaldehyde: 36 $\mu\text{g}/\text{m}^3$ after 3 days or 28 days
Blue Angel	Germany	200 or 300 $\mu\text{g}/\text{m}^3$ (28 days)	Formaldehyde: 60 $\mu\text{g}/\text{m}^3$ (28 days)
Austrian Ecolabel	Austria	1.2 mg/m^3 (3 days) 0.36 mg/m^3 (28 days)	Hexanal: 70 $\mu\text{g}/\text{m}^2\cdot\text{h}$ (28 days), nonanal: 20 $\mu\text{g}/\text{m}^2\cdot\text{h}$ after 3 days
GUT	Germany	300 $\mu\text{g}/\text{m}^3$ (3 days)	Formaldehyde: 10 $\mu\text{g}/\text{m}^3$ after 28 days
EMICODE EC1 such as adhesives	Germany	500 $\mu\text{g}/\text{m}^3$ (10 days)	Formaldehyde and acetaldehyde: 50 $\mu\text{g}/\text{m}^3$ each after 24 hours
Scandinavian Trade Standards	Sweden	Declaration of TVOC after 28 days and 26 weeks no limits specified	Formaldehyde and acetaldehyde according to WHO

Table 8

Samples 24-hour iVOCs, TVOC as toluene, between n-C6 and n-C16 emission factors including formaldehyde ($\mu\text{g}/\text{m}^2\cdot\text{h}$)¹⁴

VOCs	CAS #	114-3S			95-3S		
		A	B	Mean	A	B	Mean
Acetic acid	64-19-7	<2.0	2.9	2.9	5.1	N/A*	5.1
Hexanal	66-25-1	2.2	4.1	3.2	6.3	10.1	8.2
Alpha-pinene	7785-70-8	59.0	95.5	77.2	96.6	61.5	79.1
Beta-pinene	18172-67-3	6.4	14.3	10.3	21.3	18.3	19.8
Alpha-phellandrene	99-83-2	2.1	<2.0	2.1	5.9	7.3	6.6
3-carene	13466-78-9	8.3	22.3	15.3	7.7	19.6	13.7
Para-cymene	99--87--6	34.4	2.6	18.5	92.9	106.6	99.8
Limonene	95327-98-3	3.3	5.1	4.2	7.1	6.5	6.8
Unknown	- - -	- - -	- - -	- - -	10.5	12.4	- - -
TVOC _{alpha-pinene}	- - -	115.7	146.9	131.3	253.5	242.3	247.9
Formaldehyde	50-00-0	8.4	10.9	9.7	16.2	18.7	17.5
Acetaldehyde	75-07-0	35.9	76.5	56.2	182.0	109.6	145.8
Acetone	67-64-1	16.7	32.9	24.8	77.5	52.6	65.1

* Compound which $\mu\text{g}/\text{m}^3$ concentration is below the quantification limit allowed by ANSI BIFMA.

¹⁴**1 $\mu\text{g}/\text{m}^2\cdot\text{h}$ corresponds to $1.55 \cdot 10^3 \mu\text{g}/\text{m}^3\cdot\text{h}$

Table 9

Samples 24-hour iVOCs, TVOC as toluene, between n-C6 and n-C16 emission factors including formaldehyde ($\mu\text{g}/\text{m}^2\cdot\text{h}$)

VOCs	CAS #	190-5S			152-5S			210-7S		
		A	B	Mean	A	B	Mean	A	B	Mean
Acetic acid	64-19-7	8.7	9.0	8.8	5.9	N/A*	5.9	6.4	5.1	5.8
Hexanal	66-25-1	9.9	8.7	9.3	6.6	5.9	6.2	10.3	4.9	7.6
Alpha-pinene	7785-70-8	153.1	326.6	239.9	210.1	46.2	128.1	151.9	83.1	117.5
Beta-pinene	18172-67-3	31.6	19.5	25.5	15.6	10.1	12.9	18.6	15.8	17.2
Alpha-phellandrene	99-83-2	6.2	N/A*	6.2	N/A*	5.2	5.2	N/A*	N/A*	N/A*
3-carene	13466-78-9	21.0	21.9	21.4	77.1	13.4	45.2	19.4	13.1	16.2
Para-cymene	99--87--6	82.1	N/A*	82.1	6.0	73.5	39.8	7.1	32.2	19.6
Limonene	95327-98-3	24.1	10.5	17.3	7.2	5.3	6.2	9.9	6.4	8.1
Unknown	---	---	---		---	5.3	2.7	---	---	
TVOC _{alpha-pinene}	---	336.7	396.2	366.4	328.5	164.7	246.6	223.5	160.6	192.0
Formaldehyde	50-00-0	18.9	20.1	19.5	10.6	12.3	11.5	14.1	12.8	13.5
Acetaldehyde	75-07-0	144.2	155.9	150.0	132.9	139.5	136.2	172.3	140.2	156.3
Acetone	67-64-1	45.0	62.9	54.0	58.0	56.6	57.3	50.3	38.1	44.2

* Compound which $\mu\text{g}/\text{m}^3$ concentration is below the quantification limit allowed by ANSI BIFMA.

On the other hand, the levels of the emitted formaldehyde converted into parts per billion (ppb) are summarized in Table 10 and, as one can see, emissions are just in the order of few parts per billion. Compared to the European E1 wood products formaldehyde emission limit of 0.1 ppm (100 ppb), all five cross-laminated timber tested products had emissions 6 to 20 times lower than the E1 required emission limits, indicating that these products could be installed in any European country embracing the E1 grade. When compared to the voluntary formaldehyde emission limits for labeling (Table 7), three of the five samples meet the formaldehyde emission limits and two samples encoded as 114-3S and 190-5S would need to be tested for longer periods of time ranging from two to three days in order to be qualified for the most stringent GUT (Germany) labeling system, for which the formaldehyde emission limit is set at $10\mu\text{g}/\text{m}^3$ after three days of sample exposure in the controlled environmental chamber.

Table 10

24-hour formaldehyde emissions as a function of product types

Formaldehyde	CAS #	114-3S		95-3S		190-5S		152-5S		210-7S	
		µg/m ³	ppb	µg/m ³	ppb	µg/m ³	ppb	µg/m ³	ppb	µg/m ³	ppb
	50-00-0	19.1	15	9.1	7	19.5	16	6.1	5	5.7	5

The new formaldehyde emission limits set forth by the Californian government known under the acronym of CARB Phase I and Phase II for wood composite products particleboard, MDF, thin MDF and hardwood plywood (HWPW) with composite core (HWPW-CC) or veneer core (HWPW-VC) have been in effect since July 1st, 2012. The final formaldehyde emission limits are: 0.13 ppm (130 ppb) for thin MDF, 0.11 ppm for normal MDF, 0.09 ppm for particleboard and 0.05 ppm for both hardwood plywood (HWPW) with veneer core (VC) or composite core (CC). By comparing these limits to those from the cross-laminated timber products shown in Table 10, one can conclude that the cross-laminated timber products easily meet the most stringent CARB limits of 50 parts per billion (ppb).

C4 Conclusions and Recommendations

Five CLT products were tested for their volatile organic compounds (VOCs), including formaldehyde and acetaldehyde emissions, in order to assist architects, engineers and builders to better select construction materials with low-emitting characteristics having less impact on indoor air quality. The tested laminated products had different thicknesses and different number of glue lines. Emissions were collected after 24 hours of samples exposure in the environmental chamber.

Results did not show any correlation between individual VOCs (iVOCs), including formaldehyde and acetaldehyde or TVOC and the thickness of the cross-laminated timber panel or the number of glue lines. All five products showed very low level of iVOC and TVOC emissions; most of the detected VOCs consisted of terpene compounds originating from the soft wood material itself used to in the cross-laminated timber products.

In terms of evaluating the products impact on indoor air quality, one can easily conclude that it would be negligible if any. The five cross-laminated timber products TVOCs and formaldehyde 24-hour results were generally lower than those set forth by some European emission labeling systems even if those limits were emissions measured after 3, 10 or 28 days of sample exposure. Also, the European E1 grade for wood products formaldehyde emissions set at 0.1 parts per million (ppm) or 100 parts per billion (ppb) is 6 to 20 times higher than those measured from the cross-laminated timber products.

Comparing the limits enforced by CARB, one can conclude that the CLT products tested in this study would easily meet the most stringent CARB limit of 50 ppb. However, we recommend, when architects, builders and engineers are using CLT products other than those tested here, to validate that emissions still meet the requirements because emissions are species characteristics.



FPInnovations

570, boul. St-Jean
Pointe-Claire, QC
Canada H9R 3J9
514 630-4100

www.fpinnovations.ca



Forest Products
Laboratory

1 Gifford Pinchot Drive
Madison, WI
USA 53726
608 231-9200

www.fpl.fs.fed.us



British Softwood Lumber Council

P.O. Box 45029
Ocean Park RPO
Surrey, BC
Canada V4A 9L1
604 536-7730

www.softwoodlumber.org



AMERICAN
WOOD
COUNCIL

222 Catocin Circle SE
Suite 201
Leesburg, VA
USA 20175
202 463-2766

www.awc.org



7011 S 19th Street
Tacoma, WA
USA 98466-5333
253 565-6600

www.apawood.org

WoodWorks



Wood
Products
Council

1111 19th Street NW
Suite 800
Washington, DC
USA 20036
866 966-3448

www.woodworks.org



Forestry Innovation Investment

1130 West Pender Street
Suite 1200
Vancouver, BC
Canada V6E 4A4
604 685-7507

www.bcfii.ca

www.fpinnovations.ca



570, boul. St-Jean
Pointe-Claire, QC
Canada H9R 3J9
514 630-4100

www.fpinnovations.ca



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Laboratory

1 Gifford Pinchot Drive
Madison, WI
USA 53726
608 231-9200

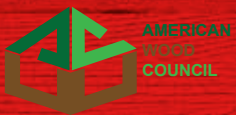
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BSLC

Woodland Softwood Lumber Council

P.O. Box 45029
Ocean Park RPO
Surrey, BC
Canada V4A 9L1
604 536-7730

www.softwoodlumber.org



222 Catocin Circle SE
Suite 201
Leesburg, VA
USA 20175
202 463-2766

www.awc.org



7011 S 19th Street
Tacoma, WA
USA 98466-5333
253 565-6600

www.apawood.org



WoodWorks

1111 19th Street NW
Suite 800
Washington, DC
USA 20036
866 966-3448

www.woodworks.org



Forestry Innovation Investment

1130 West Pender Street
Suite 1200
Vancouver, BC
Canada V6E 4A4
604 685-7507

www.bcfii.ca