MORRISON HERSHFIELD

REPORT

# Feasibility Study for 12-Storey Cross Laminated Timber Mixed Use Building

Ottawa, Ontario

Presented to:

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# 1. INTRODUCTION

## 1.1 Executive Summary

The continuing evolution of science behind climate change as a result of global warming, highlights the importance of the reduction of our carbon footprint. According to various international studies, the building industry is responsible for generation of roughly a third of greenhouse gas (GHG) emissions worldwide. High carbon and energy intensive traditional building materials such as concrete and steel dominate our construction landscape today and will continue to do so in the future. However, with a renewed sense of urgency to respond positively to the challenge of climate change, the building community is at the forefront of new innovations and technology which aim to reduce the environmental burden caused by the construction and operation of our buildings.

Cross Laminated Timber (CLT) technology has been developed as a viable alternative to traditional reinforced concrete and steel construction techniques. Developed and successfully implemented in Europe, mid to high-rise CLT buildings are widely regarded as alternatives to traditional steel and concrete ones from both economic and environmental perspectives. The Wood Products Division of FPInnovations (a non-profit organization which carries out scientific research and technology transfer for the Canadian Forestry Industry) have conducted extensive research and have developed a handbook to provide key technical information related to the manufacturing, design and performance of CLT technology.

The Canadian Forest Service-Natural Resources Canada (CFS) aims to ensure that a wood option is considered by any potential owner/project management team for any future federal building infrastructure upgrade program. Therefore, the purpose of this feasibility analysis is to assess the far-reaching implications of this technology's use in various environmental, social and economic categories. In doing so, technical input was sought from various industry sectors to gain an overall understanding of available technologies, costs and burdens associated with gaining developmental approval from numerous regulatory agencies.

The outcome of this collaborative analysis results in the conclusion that CLT can be effectively utilized as a viable alternative building materials technology to construct a 12 story mixed use building. Further in-depth analyses and testing must be conducted to demonstrate the compliance to various structural, fire and life safety measures, but, its significant environmental and economic benefits identified here can lead the way in bringing CLT to the forefront of the sustainable building industry.

## 1.2 Overview of CLT Technologies

First developed in Switzerland in the early 1990's, then adopted and modernized by Austria and Germany, Cross Laminated Timber (CLT) is a multi-layer wooden panel system made of lumber and glue.

CLT is conceptually similar to pre-cast concrete, with structural panels fabricated off site, transported to a building site, and lifted or raised and ultimately fastened together to form the structure of a building. CLT panels can be used as load bearing walls and floor slabs, interior walls, exterior walls and roof slabs. CLT can be combined with other more conventional systems (beams, columns, foundations, etc.) if required.

CLT typically consists of three to seven layers of dimensional lumber glued together in a crosswise configuration. Though it is feasible to manufacture CLT using hardwoods like poplar and engineered Oriented Strand Board (OSB), Laminated Strand Lumber (LSL), Oriented Strand Lumber (OSL) and Laminated Veneer Lumber (LVL), CLT is typically made using softwoods.

Manufacturing CLT involves three main components:

- Lumber with a moisture content of 12% (±2%), based on geographic location. The panels are kiln dried before they are trimmed, and then each panel is finger jointed with glue.
- Glue consisting of urea-formaldehyde free adhesives is utilized to laminate the face and edge surfaces to create a structurally sound bond.
- Pressure is typically applied using hydraulic presses; the glued panels are pressed together to form laminated panels. Increased size availability of mechanical presses are a benefit to CLT manufactures and designers as it helps reduce the number of CLT panel components required for final assembly on site thereby reducing the carbon footprint associated with panel transportation to site.

The final panel sizes vary depending on manufacturer and design. The maximum panel dimensions are mostly governed by the size of mechanical presses available and transportation regulations involved in shipping. Typical panel widths are 0.6, 1.2, and 2.95 meters but can be manufactured to be up to 4 meters as well. The lengths of panels are design specific and can be manufactured to be up to 24 meters in length.

An added benefit to this technology is the ability of CLT panels to be cut to size with the use of high precision CNC machines, which can make openings for windows, doors and service runs.

Various research studies have been conducted by academic, governmental and private organizations, which have together contributed to the success and acceptance of CLT technology as a viable alternative to traditional reinforced concrete and steel construction techniques. The Wood Products Division of FPInnovations (a non-profit organization carrying out scientific research and technology transfer for the Canadian Forestry Industry) has developed a Handbook to provide key technical information related to the manufacturing, design and performance of CLT. Comprehensive studies to analyze the seismic behavioral properties of CLT buildings have been undertaken by international government and research entities. A 7 story shaking table test was conducted in October 2007 at the Hyogo Earthquake Engineering Research Center in Miki, Japan. Also, a recently released ANSI/APA PRG 320-2011 Standard for Performance-Rated Cross-Laminated Timber (see Appendix B), developed by American National Standard's Association, indicates that CLT manufacturing technology is based on sound science and engineering.

Due to the inherent structural, acoustical and elastic characteristics of wood, CLT buildings can be designed and engineered to meet the performance and safety standards set forth by local and national building codes.

Using CLT technology on all levels except the ground floor, the Stadthaus – a nine-storey apartment building in London, UK – offers twenty-one apartment units and stands as a testament to the growing popularity, and feasibility (both economic and environmental) of this new innovative building product.

## 1.3 Scope of Work

The basic intent of this project was to determine the barriers to using CLT on a hypothetical 12 storey mixed use building in Ottawa, and to determine the feasibility of CLT as opposed to more conventional systems for the same building. This report also includes discussions on the benefits of using CLT relative to conventional systems.

The scope of work for this project is detailed in our proposal dated January 3, 2012 and is provided below:

- MH selected base building construction materials and systems that would reflect common materials and systems used in the Ottawa area for new construction of this building type.
- A comparable CLT building was developed to match the base building in area and type. Some modifications were made to accurately reflect the opportunities or limitations in the different building types.
- A key element of our methodology was the multi-disciplinary brain-storm meeting held in order to both communicate typical construction and material practices for CLT and to also explore potential solutions for implementation.
- Cost Estimates

   - Base building cost estimates were developed using RS Means costing tools. Initial cost estimates were verified and adjusted as necessary by a general contractor familiar with high rise construction in Ottawa.

   - CLT building cost differences were developed using RS means as a starting point and were improved using the knowledge of a general contractor familiar with high rise construction in Ottawa, as well as the assistance of CLT manufacturers.

   - Cost estimates include all associated costs, including design, code, electrical, mechanical, permits, finishes, etc. and provided representative estimates for similar elements between the two building types (such as landscaping, roofing, development fees, etc.)

   - Costing effects were delivered as a change from the base building cost and were expected to be indications of cost effects only, rather than firm quotes.

   - Certain elements of the building, and their associated costs, were developed using informed assumptions on the relative change to design and/or construction efforts. For example, concrete below grade structure is expected to be lighter for the CLT option, and an assumption on the degree of change will be made after discussions with in-house structural engineers, rather than performing a more detailed design of the two scenarios.

- Whole building energy simulation is not included, although this report comments on the thermal performance of the different assemblies and their likely impact on energy use (qualitatively).

- Life Cycle Analysis studies were performed on both the base and CLT buildings using Athena's Impact Estimator. The Impact Estimator does not include CLT materials at this time. A work-around was developed based on material volumes of wood for this purpose. The LCA study was cursory in nature and operational energy was not considered.

- Risks, opportunities, and implications of using CLT will be reported qualitatively and will be limited to the consideration of:

   - Fire issues related to construction:

      - Identified up to two possible solutions to address fire safety during construction

      - Undertook a qualitative risk analysis only, and only with respect to the areas of performance defined by the Code requirements

   - Building Code issues:

      - From available literature and projects we have identified the key fire and life safety risks associated with CLT.

  - Brainstorming sessions were held to explore possible solutions that may be developed to address the risks. No further analysis of the extent to which the risks addressed were undertaken and this time, and it is expected that further analysis will be required to support any solution.

- Constructability issues
- Trade sourcing
- Construction waste
- Scheduling
- Planning cycle issues

- The presentation will consist of a PowerPoint slide deck summarizing the study purpose, methodology and results. We will also include some introductory material associated with CLT, which we have assumed will be available from a supplier or trade association.

## 1.4 Methodology and Information Sources

A key element of our proposed methodology is a multi-disciplinary brain-storm meeting to both communicate typical construction and material practices for CLT and to also explore potential solutions for implementation.

Contractors and CLT manufactures who have previously undertaken similar studies have been contacted to gather their input and experiences.

**Project Participants and Information Sources:**

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|---|---|
| **CLT Research and Manufacture Resources** | **FPInnovations**<br>Mr. Richard Desjardins<br>Manager, Building Systems<br><br>Mr. Marjan Popovski<br>Principal Scientist & Quality Manager<br><br>**Nordic**<br>Mr. Daniel Turcotte<br>Directeur Certification & Réglementation<br><br>**Structurlam Products Ltd.**<br>Mr. Bill Downing<br>President<br><br>Mr. Michael Kascak<br>Technical Sales Support Manager |

| | |
|---|---|
| **General Contractors** | **PCL Construction Management Inc.**<br>Mr. Mark Taylor<br>Operations Manager, Toronto<br>Mr. Dan Sadler<br>Senior Project Manager, Vancouver<br>Mr. Jim Awe<br>Project Manager, Calgary |
| **Code, Fire and Life Safety** | **Morrison Hershfield**<br>Ms. Judy Jeske<br>Director, Code and Life Safety Group, Ottawa<br>Ms. Dana Scherf<br>Code Consultant, Ottawa |
| **Mechanical and Electrical Systems** | **Morrison Hershfield**<br>Mr. Paul Seguin<br>Senior Project Engineer, Ottawa |
| **Structural Analysis** | **Morrison Hershfield**<br>Ms. Mila Paramonov<br>Lead Structural Engineer, Calgary |
| **Energy Performance and Envelope** | **Morrison Hershfield**<br>Mr. Giuiliano Todesco<br>Energy Specialist, Ottawa |
| **Life Cycle Analysis** | **Morrison Hershfield**<br>Mr. Mark Lucuik |

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|---|---|
| | Director of Sustainability, Ottawa<br>Ms. Laura Paul<br>Sustainability Analyst, Ottawa |
| **Sustainability** | Morrison Hershfield<br>Mr. Kalum Galle<br>Senior Sustainability Specialist, Calgary<br><br>Ms. Maya Douglas Kingsford<br>Sustainability, Calgary |

**Other sources of information and publications:**

- CLT Handbook – Canadian Edition, FPInnovations, 2011
- ANSI/APA PRG 320-2011 Standard for Performance-Rated Cross-Laminated Timber, American National Standards Institute, 2011
- THE CASE FOR Tall Wood BUILDINGS – How Mass Timber Offers a Safe, Economical, and Environmentally Friendly Alternative for Tall Building Structures, mgb ARCHITECTURE + DESIGN, 2012
- CrossLam$^{TM}$ by STRUCTURLAM; Cross Laminated Timber Design Guide, 2011

# 2. DESIGN

A Government of Canada organization has developed a functional program and a set of construction estimates for office space requirements after the upcoming end-of-life of two major buildings in the National Capital Region. This planning and costing information does not currently include a structural option using wood building materials. The Canadian Forest Service-Natural Resources Canada (CFS) aims to ensure that a wood option is considered by any potential owner/project management team, alongside the reinforced concrete option. In order to do so, construction estimates were drafted for a 12 storey mixed use building consisting of a 2500 $m^2$ floor plate, constructed in cross-laminated timber (CLT), with two storeys of underground parking.

| Building Component | Benchmark Design | CLT Design |
|---|---|---|
| **Gross Floor Area (GFA)** | 30,000 $m^2$ | 30,000 $m^2$ |
| **Design Life** | 75 years | 75 years |
| **Foundation** | reinforced concrete | reinforced concrete |
| **Parkade** | 2 storey reinforced concrete | 2 storey reinforced concrete |
| **Floor Structure** | reinforced concrete | cross laminated timber (CLT) |
| **Vertical structure** | reinforced concrete beams and columns | load bearing CLT interior and exterior walls, glulam columns & beams |
| **Exterior Walls** | insulated curtainwall with steel stud and gypsum board | insulated curtainwall over CLT |
| **Roofing System/Insulation** | conventional insulated modified bitumen roof assembly | conventional insulated modified bitumen roof assembly |

## 2.1 Site and Geological Considerations

Due to reduced dead loads associated with CLT structures vs. traditional reinforced concrete buildings, the foundations would be smaller in almost any soil conditions. Previous projects in both Europe and Canada demonstrate that neighborhoods and campuses with CLT constructed buildings greatly benefited from a much shorter construction period and a reduction in construction related traffic. Due to the proximity of the hypothetical project location to a body of water, prominent established residential neighborhoods, and the associated site conditions, these benefits offered by CLT could be significant compared to conventional construction.

## 2.2 M&E System Requirements

Typically HVAC, electrical and water distribution systems are integrated into the suspended ceiling space. More in-depth attention to aesthetic design is needed to integrate the M&E system as exposed timber faces may add an additional aesthetic appeal to occupants. Sleeveing through structural load bearing CLT walls and beams to accommodate large ducts and other M&E components may adversely affect the structural integrity. Therefore, for the purpose of this study, ductless equipment or pumped refrigerant systems combined with a dedicated ventilation system is recommended. Furthermore, a raised floor distribution system may be ideal to suit the flexibility of space re-configurations in the future.

## 2.3 Code, Fire and Life Safety Issues and Possible Solutions

### 2.3.1 Regulatory Approval for CLT

Any CLT building will be required to demonstrate compliance with the current National Building Code of Canada (NBC). There are two ways to meet the NBC – either by complying with the acceptable solutions in Division B, or, by using an alternative solution that will achieve the same level of performance as outlined in Division B.

Despite the alternative solution compliance option clearly stated in the NBC, significant challenges can be faced in demonstrating equivalent performance for a 12-storey building constructed with CLT. First and foremost, CLT is a combustible material and Subsection 3.2.2. of the NBC Division B clearly requires any building over 4 storeys to be of noncombustible construction. Other related restrictions on the use of combustible materials in certain applications include the construction of fire separations around exits and vertical service spaces (Sentence 3.1.5.13.(3)).

Hence, an alternative solution for a CLT building would need to perform at a level equivalent to that of a building constructed of a noncombustible material. The performance would need to be demonstrated in the areas of the functional statement and objectives linked to the Division B requirement to be noncombustible, [F02-OS1.2] and [F02-OP1.2]:

- F02 To limit the severity and effects of fire or explosions.
- OS1.2 An objective of this Code is to limit the probability that, as a result of the design or construction of the building, a person in or adjacent to the building will be exposed to an unacceptable risk of injury due to fire caused by fire or explosion impacting areas beyond its point of origin.

- OP1.2 An objective of this Code is to limit the probability that, as a result of its design or construction, the building will be exposed to an unacceptable risk of damage due to fire caused by fire or explosion impacting areas beyond its point of origin.

Two intent statements are linked to the requirement to be noncombustible:

- To limit the probability that combustible construction materials within a storey of a building will be involved in a fire, which could lead to the growth of fire, which could lead to the spread of fire within the storey during the time required to achieve occupant safety and for emergency responders to perform their duties, which could lead to harm to persons.

- To limit the probability that combustible construction materials within a storey of a building will be involved in a fire, which could lead to the growth of fire, which could lead to the spread of fire within the storey during the time required to achieve occupant safety and for emergency responders to perform their duties, which could lead to damage to the building.

To summarize, the Division B provisions for noncombustible construction for buildings greater than 4 storeys in height are intended to limit the probability that combustible construction materials will be involved in a fire since this may lead to greater fire growth or fire severity which could harm persons or damage the building. It is noted that the Division B requirement to be noncombustible is not directly linked to structural capacity of the material or to the provision of a specified fire resistance rating. Although these issues are related, and CLT performance in these areas will need to be demonstrated, compliance with Division B is the likely compliance path for the issues of structural performance (e.g. Part 4 compliance) and fire resistance ratings (see further discussion in next section of this report).

The challenge for a 12 storey CLT building will be to demonstrate that its performance in "limiting the severity and effects of fire" is equivalent to that of a noncombustible building. The key difference between these building types with respect to "limiting the severity and effects of fire" is the potential for the structure to be involved in the fire, i.e. to contribute to fuel load and therefore fire growth, the potential to have reduced structural capacity once involved in a fire, and the potential for additional smoke generation from the burning of structural members. Structural elements in noncombustible buildings will not contribute to fuel load alone, but their structural capacity can be reduced if fire protection is compromised (e.g. protective covering for steel is damaged or removed).

To establish a benchmark for comparison between acceptable solutions, the performance level of a 12 storey building of noncombustible construction will need to be documented. Then the performance level of a 12 storey CLT building will need to be demonstrated. This will be a holistic exercise examining the building design as a whole since fire protection involves multiple building systems and design strategies that are used in combination to achieve an acceptable level of safety appropriate for the building size and occupancy. Passive fire protection includes using noncombustible building materials, compartmentalization with fire separations, application of surface flame retardants, and protection of combustible surfaces with gypsum board. Active fire protection includes automatic sprinklers and other suppression systems. Performance with respect to occupant safety, emergency responder safety, and property protection will need to be assessed.

One or more compensating features, such as protection of the CLT by gypsum membranes (if not already in place to achieve fire resistance ratings), increased compartmentalization, early detection capabilities of the fire alarm system, or increased responsiveness and density of sprinkler protection, could be analyzed for their ability to offset the risks arising from combustible construction. Protection by gypsum membranes may reduce the risk of ignition and involvement of the CLT in a fire. Increased compartmentalization may reduce fire size and slow fire spread to other compartments. Early detection may facilitate early occupant evacuation and emergency response. Increased sprinkler system performance may control a fire faster and reduce smoke and heat production.

Since fire protection features are interrelated, evaluation of the whole building using a recognized and validated risk assessment method may be the most appropriate way to demonstrate performance for a comprehensive alternative solution for a 12 storey CLT building. Another method to evaluate the alternative solution is to undertake whole scale computational fire modeling to assess the performance of wood under fire conditions as well as separate analysis of the performance of wood construction under structural loads. Although advanced computation fire models are available and are in wide-spread use as a fire protection engineering tool, significant limitations apply to these models. One of the most significant limitations is the ability to correctly model the effectiveness of sprinklers. Many models rely on overly conservative assumptions that, when compounded, may undermine the analysis as a tool to assess the performance of a material that would otherwise not be permitted by the NBC.

If the 12 storey CLT building is designed with the top floor level less than 36 metres above grade it will not be considered a "high building", but at 12 storeys it may be close to the definition. While high building requirements of Division B do not directly relate to the requirement to be noncombustible, a high building or almost-high building will have increased challenges for occupant evacuation, smoke control, firefighter safety and suppression activities, and these will need to be considered in the analysis of an alternative solution.

The analysis and preparation of supporting documentation for an alternative solution will add time to the design/pre-construction phase of a 12 storey CLT building. This may, however, be facilitated if similar CLT projects are approved in Canada ahead of this project. The approval process with the Authority Having Jurisdiction (AHJ) is also expected to increase the design/pre-construction phase relative to a building of conventional construction. The approval process will be facilitated if the design team and the AHJ can establish open and direct communication early in the project planning stages.

An Authority Having Jurisdiction is obligated to review a proposed alternative solution, but the onus is on the proponent to demonstrate the same level of performance as Division B. It may be helpful to provide documentation of cases where a similar alternative solution has received approval in another jurisdiction. Nonetheless, since alternative solutions are site specific there is no mechanism in the Codes that makes approved alternative solutions elsewhere in Canada precedents for subsequent projects.

Similarly, referencing approved CLT projects in other countries may be helpful in the development and support an alternative solution for a Canadian building. However, since building codes in other countries are "performance-based", and the Canadian codes are "objective-based", international examples may not be comparable to the performance level required by the NBC for an alternative solution for a 12 storey CLT building.

It is not possible to guarantee that an alternative solution will be successful at any point in time since final approval is subject to the judgment of the AHJ. Keeping in mind the size of the CLT building the alternative solution will be inherently complex and will require significant effort by more than one party to develop and fully analyze the alternative solution prior to submission to the AHJ, and likely during the review process through a peer review process.

### 2.3.2 Key Fire and Life Safety Risks Identified for CLT

The performance of CLT under fire exposure is currently being researched and tested by numerous agencies and organizations in Canada and around the world. Designers and CLT manufacturers have demonstrated adequate performance under fire exposure in other countries as there are many examples of buildings constructed of CLT.

In Canada, the performance of CLT will need to be demonstrated to meet Canadian Standards as referenced in the National Building Code. For a 12 storey building, performance in these key areas will need to be demonstrated:

- 2 hour fire resistance rating for CLT floor assemblies and loadbearing elements based on CAN/ULC-S101 "Fire Endurance Tests of Building Construction and Materials"
- Flame spread ratings and possibly smoke developed classification of exposed CLT elements based on CAN/ULC-S102 "Test for Surface Burning Characteristics of Building Materials and Assemblies"
- Firestop system performance for service penetrations through CLT fire separations based on CAN/ULC-S115 "Fire Tests of Firestop Systems"

Analytical methods are being developed to calculate the fire resistance rating of CLT assemblies; however these will need to be validated by testing. Even if unprotected CLT assemblies are shown to provide a 2 hour fire resistance rating, CLT assemblies may be designed to be "encapsulated" or protected by gypsum board in order to provide an additional level of safety, perhaps as a measure in the alternative solution. Protection of CLT by gypsum board may also be desired for service rooms and parts of the means of egress such as exits, lobbies and corridors.

Based on a review of literature and projects to date, results for fire performance relative to Canadian standards are not yet published, although agencies involved in the testing have indicated that the results are positive. Inherent in the testing and validation process will be demonstration of the performance of elements integral to CLT construction such as fire performance of the adhesives used in CLT, and fire performance of the steel connections.

### 2.3.3 Fire Safety During Construction

The National Fire Code (Section 5.6.) contains construction fire safety provisions applicable to all construction projects, and some of these requirements are especially important for buildings of combustible construction. Fire risks during construction of a combustible building include combustible materials being exposed since gypsum or other protection is not yet in place, sprinkler systems are not yet operational, and construction activities typically include heat sources and sources of ignition. These risks can be managed by meeting Fire Code requirements, following established safety procedures and implementing enhanced safety measures such as increased security after hours and increased supervision of hot work.

The basic fire risks associated with CLT construction will be similar to those in conventional combustible construction in many ways, except CLT is generally in a slab-like configuration as a solid mass as opposed to small dimensional lumber such as wood joists or plywood sheets. It is worth nothing that the slab-like characteristic of CLT will reduce the risk of ignition relative to conventional lumber, and will alter the fire characteristics if a fire is ignited.

Another fire safety risk to be considered for a 12 storey CLT building is the risk of a fire during construction at heights greater than 4 storeys. The increased height will be a challenge for suppression and firefighting. The increased risk due to construction of a combustible structure at greater than 4 storeys in building height during construction may be addressed by a combination of measures. These measures could include establishing limits on the amount of exposed CLT during any one construction stage, by strict limitations on where hot work can occur, by requirements to have fire suppression systems installed and active by a certain stage, or by a requirement to have active fire suppression capabilities nearby during critical stages of construction. A construction safety plan will need to be developed and agreed to by all parties in the process including the building owner, contractor, the Fire Department and the AHJ.

## 2.4 Design and Tendering

A significant benefit in CLT technology is the rapid construction related efficiencies and the associated financial cost savings. However, early adopters of CLT technology in Canada are to be aware that traditional approach to design and tendering will not be efficient or cost-effective as the manufacturing of CLT panels cannot commence until the contract is awarded. The lead times associated with the CLT manufacturing process will, in most cases, encumber a traditional construction schedule for a common design-bid-build model.

To improve efficiency and minimize construction time, the CLT manufacturer should be selected early in design, and the manufacturing of CLT panels begun before award of the construction project. Accordingly, Construction Management (CM) or Design-Built (DB) approaches should be considered. Traditional, often lengthy public tendering processes will be detrimental to the construction related efficiencies associated with CLT construction projects.

In both Construction Management (CM) and Design Build (DB) scenarios the contractor and CLT manufacturer can work directly with the designers and have the opportunity to influence the design based on constructability and material properties. This process will significantly improve the time and costs associated with construction as the design and manufacturing of CLT panels would be done in parallel and will arrive at site ready to be assembled. This would also significantly reduce the bid drawings packages and re-engineering work typical to traditional construction. Alternatively, a CLT manufacturer can be selected early in the design process before the design drawings are finalized to provide design assistance services.

# 3. CONSTRUCTABILITY

## 3.1 Scheduling

Rapid constructability due to modular assembly of pre-fabricated CLT panels is one of the main attributes of CLT which in turn reduces the capital cost associated with site related labour. This typically results in faster project turnarounds. Once the structural requirement of re-shoring, which can be up to five to six weeks for traditional reinforced concrete construction, is no longer a hindrance due to the use of CLT flooring, further schedule improvements can be expected.

## 3.2 Tools, Expertise, and Detailing

The devised method of construction may influence final success in a building constructed exclusively with CLT. A recently published study of Tall Wood Buildings by mgb Architects, with participation from representatives of all major construction industry sectors, has developed a tilt-up method more suitable for a modular panelized system. To benefit the construction efficiencies related to this type of construction, utilization of an on-site tower crane or multiple mobile lifting systems, are identified as a major element in their study. However, an urban site would create a special challenge as the modular nature of CLT construction would require large off-site staging and storage area to deliver the pre-assembled components in a seamless and efficient manner to the installers.

Re-education and re-training will be expected for traditional carpentry related trades to make the adjustment to high-rise construction practices. Because of their expertise in pre-fabricated and modular construction practices it may be economically preferable to utilize heavy formwork contractors to erect CLT structures. Additionally, in most cases, CLT manufactures can take on the additional scope of installation and this can significantly reduce risk associated to the general contractor.

Importantly, prolonged exposure of CLT panels to moister during construction can adversely affect the structural integrity and indoor air quality of the building. Temporary coating products which are readily available in the market can be utilized to mitigated moisture related challenges. Following from this, it is important for general contractors to develop systems to safeguard wood assemblies.

Ideally, construction teams should use an enclosure to minimize water/moisture penetration. Alternatively, an overhead canopy attached to an external superstructure can be raised as the building is being constructed, although the cost of this approach extend from those typically associated with traditional construction and fall under maintenance of the structural and indoor environmental integrity of the building.

This type of approach was successfully utilized in Sweden during the construction of the 8-storey Limnologen building in Växjo. Similarly, the Murray Grove project in London utilized a temporary scaffolding system with a weather barrier wrapped around the building. By eliminating weather related delays, both methods were also credited for an increase in construction efficiency.

## 3.3 Costing

In comparing the cost implications for a CLT based structure to a traditional reinforced concrete construction, common elements associated with each method (i.e. site work, curtain-wall, parkade , vertical transportation, interior finishes, mechanical and electrical systems) were treated as cost neutral and therefore, not considered. The cost considerations below present only differences between the conventional and CLT systems.

| | 322,900 Sq.ft (30,000 m²) | |
|---|---|---|
| | Reinforced Concrete | CLT |
| **Foundation** | $2.30/Sq.ft | $1.70/Sq.ft |
| **Columns and Beams** | $18.00/Sq.ft | $23.00/Sq.ft |
| **Slabs** | $12.00/Sq.ft | $16.00/Sq.ft |
| **Shafts/Core Walls** | $18.00/Sq.ft | $20.00/Sq.ft |

This cost estimate have taken account the costs for labour, materials, equipment and other contingencies but, does not include the costs associated with engineering and design. Typical commercial construction costs rages between $200 and $250 per square foot. The above analysis of core component price difference indicates a 17% cost increase. However, it is important to note that significant cost savings can be achieved with CLT construction due to reduced construction times and crews.

Utilization of CLT panels would allow the floor and ceiling surfaces to be kept exposed to further showcase the inherent esthetic characteristics of wood and at the same time, significantly reduced the additional costs associated with drywall finishes. However, costs associated with moisture protection measures should be taken into consideration with CLT.

# 4. ENVIRONMENTAL AND SUSTAINBILITY BENEFITS

## 4.1 Environmental

### 4.1.1 Energy Performance

Thermal wall requirements of commercial buildings in Canada range from a low of ~RSI 1.2 (~R7) under the MNECB guideline for the province of British Columbia to RSI 3.3 (~R19) in Ontario under the new SB-10 prescriptive requirements. Good practice would in general dictate a range of RSI 2.6 to 3.3 (R15 - R20).

The thermal performance of CLT is listed as being RSI 0.7 (R4.2) for a typical 89 mm (3 ½ in) thick panel. This performance level would require an additional 50 to 100 mm (2 to 4 in), of rigid insulation to reach the required thermal performance levels mentioned above. In order to protect the CLT from moisture damage and exposure to the elements, best practices dictate placement of the insulation on the exterior. This approach renders the CLT system a type of EIFS system with the advantage of an interior finish that does not require an additional layer of gypsum board unless fire codes dictate otherwise.

Relative to other lightweight wall systems, the CLT/EIFS wall system would display less thermal bridging and therefore require less insulation for the same effective wall R-value of a comparable stud wall system.

Ultimately, the conventional wall system could have the same thermal resistance of the CLT system, but it would need approximately 25 mm of additional insulation to do so due to the thermal resistance of the CLT panels.

### 4.1.2 Life Cycle Analysis

Life Cycle Assessment (LCA) is becoming an accurate and widely accepted scientific method of quantifying the overall environmental impact of a product through its entire life from resource extraction through product manufacturing, transportation, construction, occupancy and the end of life demolition including disposal. The designers can extrapolate this information to gain an understanding of the material choices they make and the associated environmental impacts.

Though many LCA tools have been developed over time, for the purpose of this study, environmental material effects of the entire buildings were estimated using Athena Institute's Environmental Impact Estimator (EIE) software (version 3.0.2). It is important to understand that entire building results should not be considered as complete. Our focus was on the difference in the designs rather than ensuring the whole building effects were accurate. Many materials, such as finishes, M&E materials, and in some instances materials not supported by Athena, were excluded from the models. However, these materials would be consistent between the steel and wood based designs for each building, leading to reasonably accurate comparison of results.

The following information is an overview of the technical details of Life Cycle Analysis from the Athena Software; a significant amount of the information comes from the Athena website as well as the Athena Impact Help Topics.

LCA is the performance approach to sustainable product or building design. It is the logical evolution from today's reliance on prescriptive methods, whereby materials are deemed to have environmental benefits based on their attributes. For example, recycled content, rapid renewability, and local procurement are all assumed to be environmentally superior characteristics without any supporting data.

LCA measures actual performance, removing the assumptions. It is widely accepted in the international environmental research community as an appropriate method for scientific quantification of an environmental footprint.

**Environmental Impact Measures**

In LCA, information is gathered at every phase of a product's life, and viewed through the lens of defined environmental impact measures. LCA reports on these environmental effects due to a product, building or service:

- **Fossil Fuel Depletion**: Fossil Fuel Consumption is reported in mega-joules (MJ). Embodied Fossil Fuel Consumption includes all energy, direct and indirect, used to transform or transport raw materials into products and buildings, including inherent energy contained in raw or feedstock materials that are also used as common energy sources. (For example, natural gas used as a raw material in the production of various plastic (polymer) resins.) In addition, the Impact Estimator captures the indirect energy use associated with processing, transporting, converting and delivering fuel and energy plus the operating energy.

- **Raw Resource Use:** Raw resource use can be measured in common units such as tonnes, but a unit of one resource like iron ore is not at all comparable to a unit of another resource like timber or coal when it comes to environmental implications of extracting resources. Since the varied effects of resource extraction, (e.g., effects on bio-diversity, ground water quality and wildlife habitat, etc.) are a primary concern, we want to make sure they are taken into account. The problem is that while these ecological carrying capacity effects are as important as the basic life cycle inventory data, they are much harder to incorporate for a number of reasons, especially their highly site-specific nature.

Athena's approach was to survey a number of resource extraction and environmental specialists across Canada to develop subjective scores of the relative effects of different resource extraction activities. The scores reflect the expert panel ranking of the effects of extraction activities relative to each other for each of several impact dimensions. The scores were combined into a set of resource-specific index numbers, which are applied in the Impact Estimator as weights to the amounts of raw resources used to manufacture each building product. The Weighted Resource Use values reported by the Impact Estimator are the sum of the weighted resource requirements for all products used in each of the designs. They can be thought of as "ecologically weighted kilograms", where the weights reflect expert opinion about the relative ecological carrying capacity effects of extracting resources. Excluded from this measure are energy feedstocks used as raw materials. Except for coal, no scoring survey has been conducted on the effects of extracting fossil fuels, and hence, they have been assigned a score of one to only account for their mass. The weighting factor for each raw material is set out below:

**Weighted Resource Use**

Weighted Resource Use is the same as normal resource converted to mass quantities except:

1. LIMESTONE * 1.5
2. IRON ORE * 2.25
3. COAL * 2.25
4. WOODFIBER * 2.5

- **Global Warming Potential (GWP):** Global warming potential is a reference measure. The methodology and science behind the GWP calculation can be considered one of the most accepted LCIA categories. GWP will be expressed on an equivalency basis relative to $CO_2$ – in kg or tonnes $CO_2$ equivalent.

Carbon dioxide is the common reference standard for global warming or greenhouse gas effects. All other greenhouse gases are referred to as having a "$CO_2$ equivalence effect" which is simply a multiple of the greenhouse potential (heat trapping capability) of carbon dioxide. This effect has a time horizon due to the atmospheric reactivity or stability of the various contributing gases over time.

As yet, no consensus has been reached among policy makers about the most appropriate time horizon for greenhouse gas calculations. The International Panel on Climate Change 100-year time horizon figures have been used here as a basis for the equivalence index:

$CO_2$ Equivalent kg = $CO_2$ kg + ($CH_4$ kg x 23) + ($N_2O$ kg x 300)

While greenhouse gas emissions are largely a function of energy combustion, some products also emit greenhouse gases during the processing of raw materials. Process emissions often go unaccounted for due to the complexity associated with modeling manufacturing process stages. One example where process $CO_2$ emissions are significant is in the production of cement (calcination of limestone). Because the Impact Estimator uses data developed by a detailed life cycle modeling approach, all relevant process emissions of greenhouse gases are included in the resultant global warming potential index.

- **Acidification Potential:** Acidification is a more regional rather than global impact effecting human health when high concentrations of NOx and $SO_2$ are attained. The AP of an air or water emission is calculated on the basis of its H+ equivalence effect on a mass basis.

- **Human Health (HH) Criteria Air-Mobile:** Particulate matter of various sizes (PM10 and PM2.5) have a considerable impact on human health. The EPA has identified "particulates" (from diesel fuel combustion) as the number one cause of human health deterioration due to its impact on the human respiratory system – asthma, bronchitis, acute pulmonary disease, etc. It should be mentioned that particulates are an important environmental output of plywood product production and need to be traced and addressed. The Institute used TRACI's "Human Health Particulates from Mobile Sources" characterization factor, on an equivalent PM2.5 basis, in our final set of impact indicators.

- **Aquatic Eutrophication Potential:** Eutrophication is the fertilization of surface waters by nutrients that were previously scarce. When a previously scarce or limiting nutrient is added to a water body it leads to the proliferation of aquatic photosynthetic plant life. This may lead to a chain of further consequences ranging from foul odours to the death of fish. The calculated result is expressed on an equivalent mass of nitrogen (N) basis.

- **Ozone Depletion Potential (ODP):** Stratospheric ozone depletion potential accounts for impacts related to the reduction of the protective ozone layer within the stratosphere caused by emissions of ozone depleting substances (CFCs, HFCs, and halons). The ozone depletion potential of each of the contributing substances is characterized relative to CFC-11, with the final impact indicator indicating mass (e.g., kg) of equivalent CFC-11.

- **Photochemical Ozone Formation Potential (Smog):** Under certain climatic conditions, air emissions from industry and transportation can be trapped at ground level where, in the presence of sunlight, they produce photochemical smog, a symptom of photochemical ozone creation potential (POCP). While ozone is not emitted directly, it is a product of interactions of volatile organic compounds (VOCs) and nitrogen oxides (NOx). The “smog” indicator is expressed on a mass of equivalent NOx basis.

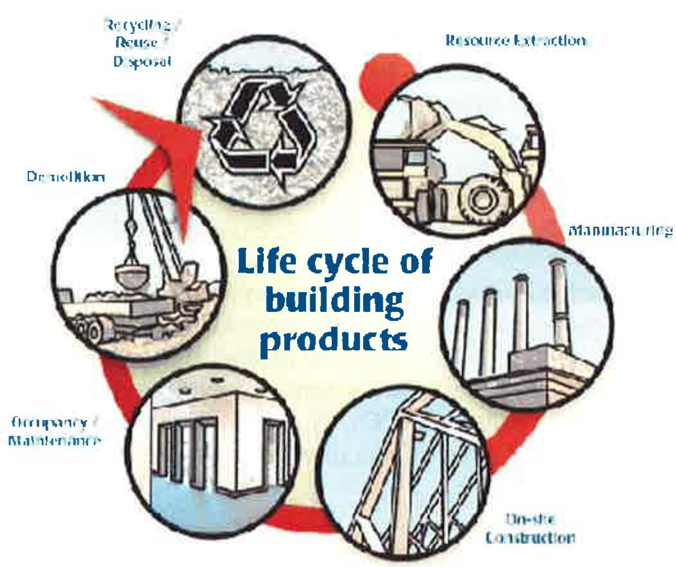
In LCA terminology, the effects associated with making, transporting, using and disposing of products are referred to as ‘embodied effects’, where the word “embodied” refers to attribution or allocation in an accounting sense as opposed to true physical embodiment. All of the extractions from and releases to nature are embodied effects, and there are also embodied effects associated with the production and transportation of energy itself (known as pre-combustion effects). Note that all phases, but the “use” phase in particular, includes environmental accounting of associated activities and their products such as periodic cleaning and repainting. For example, a life cycle assessment for a deck needs to include the energy, water use and detergents involved with cleaning, the various impacts associated with coating products like stain, and the possible replacement of some boards over the life of the deck.

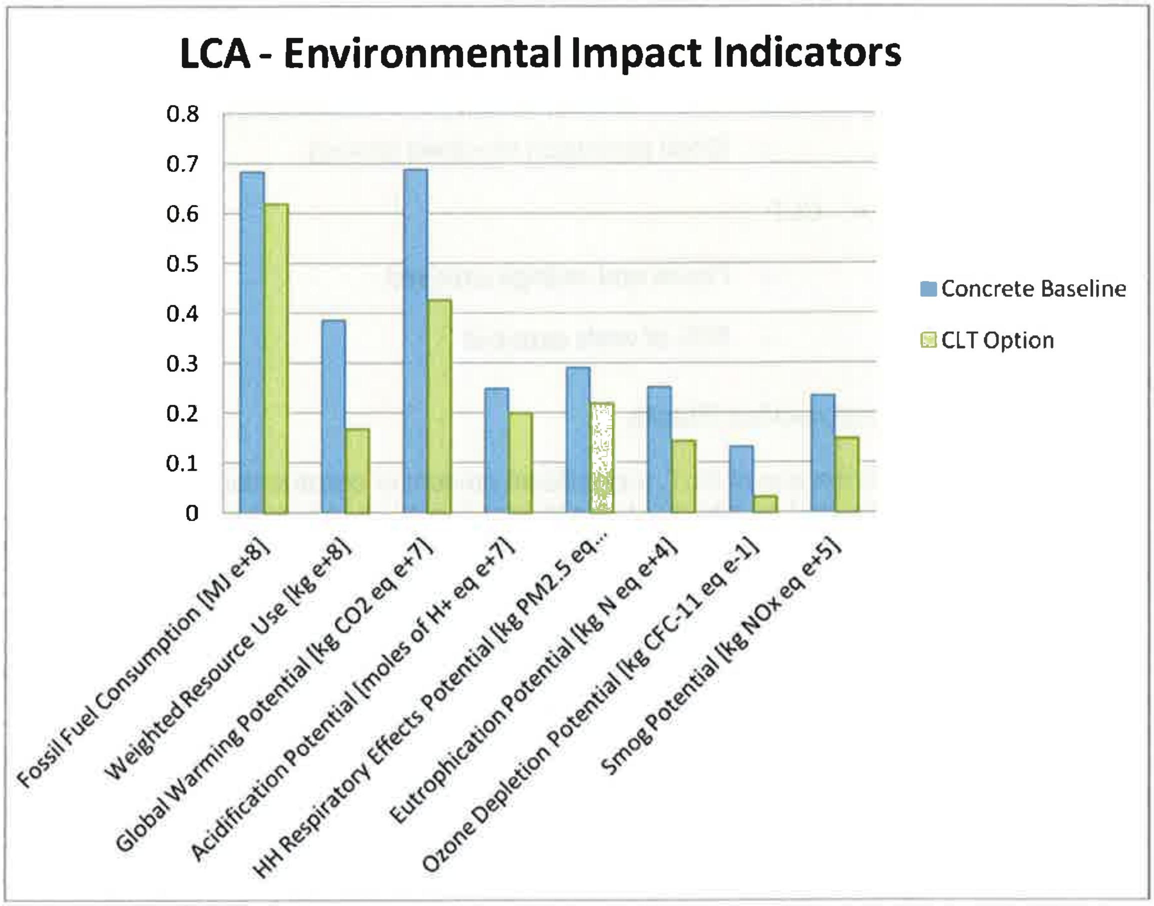
**Life Cycle Phases within LCA**

The Athena Impact Estimator is a tool with detailed life cycle assessment in the background that provide access to LCA results on building products and report results for a building or assembly. Impacts are reported as a whole or broken down by six life cycle phases:

1. Resource extraction
2. Product manufacturing
3. Construction of the building
4. Building Occupancy and maintenance
5. Building demolition
6. Materials disposition (disposal or transfer for recycling or reuse)

See the diagram below and detailed description of the six life phases.






***Please refer to Appendix A for full Athena Summary Measure Tables by Life Cycle Stages***

As it can be seen from the graphic above, the CLT building offers noticeable reductions in environmental impact over all of the impact categories. Accordingly, from an environmental effects of materials perspective it should be preferred choice

**Assumptions made for Athena LCA model:**

- 100 year design life
- Project location: Ottawa Ontario
- Multi-Unit owner occupied
- 40% viewable glazing, 60% spandrel panel
- 100mm insulation, with metal cladding
- 3.6 m floor heights
- Concrete Baseline

  - Steel stud and gypsum walls
  - Gypsum ceilings, painted
  - Small dimension kiln dried flooring
- CLT
  - Floors and ceilings exposed
  - 50% of walls exposed

### 4.1.3 Construction Waste

With the use of CLT, a significant amount of construction waste, typically generated on-site due to traditional construction activities can be diverted from landfills. Primarily due to prefabricated nature of CLT construction, and reduced number trades associated with finishes, waste generated on-site and related hauling and dumping cost would be reduced significantly. Furthermore, highly reusable nature of lumber would significantly reduce material wastage due to cutting and sizing. The reduced effects of waste are included in the LCA analysis above.

### 4.1.4 Site Impacts

Indoor Air Quality issues during construction such as dust, noise and site disruptions would be considerably reduced in a project utilizing CLT technologies. Constant arrival and departure of concrete trucks would be entirely eliminated once the foundation work is complete. Erosion and sedimentation issues such as mud tracking generated due to heavy vehicular traffic would be dramatically reduced due to pre-fabricated nature of CLT construction technologies and associated reduction in on-site personal involvement. Less vehicular and noise related disruptions would improve the negative effects historically associated with construing sites and their surrounding neighborhoods. These effects, although significant, are not included in the LCA analysis above.

## 4.2 Social

### 4.2.1 Sustainably Harvested Lumber

Lumber can be harvested using different ecosystem-relevant methodologies with a range of environmental impacts. Canada's sustainable forest management legal and regulatory framework is complemented by independently audited, third-party certifications systems in the forest industry that promote continuous improvement in environmental, social and economic performance. Canada has become the world leader in third party forest certification with 42% of certified forest operations worldwide whereas globally, only 10% of forest operations are independently certified.

### 4.2.2 Comfort and Aesthetic Quality

Having undergone extensive testing in both in Europe and Canada, CLT assemblies were observed to behave similarly to other traditional building components and systems in analyzing the acoustical qualities. Both Sound Transmission Class (STC) and Impact Insulation Class (IIC) requirements for local and national building codes can be met by designing the relevant components in accordance to the requirements. Moreover, an air-tight construction and integration of sound absorption layers can further increase the acoustical qualities of the space.

With its inherently low thermal conductivity and its nature as a panel system, CLT offers reduced effects of thermal bridging (as compared to steel or concrete) thereby reducing the likelihood of condensation and associated drafts.

From a thermal mass perspective, the CLT and concrete buildings would have a fairly high ability to store thermal energy, whereas a steel building would have a relatively low thermal mass. High thermal mass buildings can temper sudden temperature changes, making the interior spaces more consistent and comfortable.

## 4.3 Economic

As previously indicated in the Costing section, when taken in to account the cost savings associated with shorter construction schedule and energy cost savings associated with a tighter building envelope and higher thermal mass, structures made with CLT can realize significant cost savings through construction and operational lifecycle of the building. However, due to its infancy, the CLT market remains uncompetitive and lack of inherent knowledge within the construction industry can lead to inflated contingencies at startup. Ultimately, the competitiveness in the Canadian marketplace will govern the success of this new technology and its future innovations.

### 4.3.1 Labour Considerations

From harvesting to manufacturing, CLT remains a fairly labour intensive process and would offer significant social and economic benefits in keeping people employed. Due to the fewer number of CLT manufacturers in North America, vast majority of the labour associated with manufacturing of CLT would take place in Canada; where strong labour laws and standards would ultimately result in a superior quality product in comparison to other materials which are manufactured in countries with reduced emphasis on standards and quality such as steel exported from China.

## 4.4 Green Building Considerations

Green Building Rating Systems such as LEED® (Leadership in Energy and Environmental Design) and Green Globes® have become a popular tool in the building industry to measure, quantify and benchmark the sustainable design and operational strategies incorporated into a building project. These two rating systems, along with many other internationally accepted ones have recognized the sustainable benefits of wood products and have developed evaluation criteria based on the following relevant categories:

- **Construction Waste:** primarily due to prefabricated nature of CLT assemblies and a significant reduction in mass heavy concrete and steel, use of CLT technology will enable projects to reduce the demolition and construction waste from landfills.

- **Resource Reuse:** incorporation of wood based building materials and components enable project teams to reduce the demand for virgin materials; thereby, reducing the waste and incentive for components to be design for disassembly.

- **Regional Materials**: use of CLT technologies from regional sources can greatly improve local timber manufacturing industries while reducing the environmental burden associated with carbon and GHG intensive transportation methods. Use of Life Cycle Assessment tools can further quantify the reduced environmental impact of regionally manufactured materials by evaluating the impacts of extraction, harvesting and shipping of raw materials.

- **Certified Wood:** Canadian CLT products are manufactured with wood harvested from sustainable sources certified through various national and international standards for responsible forest management practices. For LEED®, this only applied to FSC (Forest Stewardship Council) certified products, but Green Globes® have included certifications from SFI (Sustainable Forestry Initiative), and CSA-SFM (Canadian Standards Association's Sustainable Forest Management Program).

- **Environmental Purchasing:** CLT creates lesser environmental impacts in terms of water use, global warming potential, smog creation, neutrification / eutrophication of water bodies, acidification, and toxic releases to air, water and land.

- **Durability, Adaptability, Disassembly:** governed by the design, a CLT building will be more adaptable (for renovations or additions) and is able to be disassembled compared to concrete. The disassembled CLT can then be re-used for other projects.

- **Materials with Low Environmental Impact**: Low Impact Systems and Materials and Minimal Consumption of Resources are two areas deal with selecting products with the lowest embodied energy and life cycle environmental burden. From an LCA perspective, compared to other materials such as steel and concrete, CLT requires less energy throughout its life cycle (resource extraction, manufacturing, distribution, use and end-of life disposal). From a GHG perspective, CLT stores carbon and will continue to store carbon for the lifetime of the product – possibly longer if the CLT product is reclaimed and used in another project.

- **Energy:** CLT offers better thermal resistance properties that comparable systems, and can therefore be relied upon to improve the insulating properties of an exterior wall or roof. This effect can lower the operational energy in a building.

- **Low-Emitting Materials**: CLT is manufactured using phenol-formaldehyde resins; and therefore, bonding glues readily used in the CLT manufacturing process do not contain added urea-formaldehyde. However, steps must be taken to prevent growth of fungus, mould, bacteria or other microorganisms which can be associated with prolonged exposures of CLT components to external elements.

- **Acoustic Comfort:** only addressed through Green Globes at this time; well-designed CLT assemblies have proven to perform well acoustically. An air-tight construction and integration of sound absorption layers can further increase the acoustical qualities of the space.

- **Innovation in Design:** the use of CLT technology over conventional construction methods and materials will continue to power the forestry/wood industry to innovate in both materials and knowledge. Waste generated by wood products manufacturing is approaching the covenant 'zero waste' threshold in Canada. 97% of all the wood fiber harvested here is turned into products, and the residuals and waste biomass turned into fuel. *(Canadian Wood. Renewable by Nature. Sustainable by Design, Canadian Wood Council Publication, October 2009).*

# 5. ADDITIONAL RESEARCH RECCOMENDATIONS

Our work on this project resulted in many answers but also many questions. We strongly suggest that additional work be performed on CLT to reduce barriers and to demystify the precut, thereby enabling increased use of the system in Canada. A number of suggestions are provided below:

- Additional research and testing to demonstrate 2 hour fire resistance rating for CLT floor assemblies and loadbearing elements based on CAN/ULC-S101 "Fire Endurance Tests of Building Construction and Materials"
- Additional research and testing to demonstrate flame spread ratings and possibly smoke developed classification of exposed CLT elements based on CAN/ULC-S102 "Test for Surface Burning Characteristics of Building Materials and Assemblies"
- Additional research and testing to demonstrate firestop system performance for service penetrations through CLT fire separations based on CAN/ULC-S115 "Fire Tests of Firestop Systems"
- Additional research and testing to demonstrate the performance of elements integral to CLT construction such as fire performance of the adhesives used in CLT, and fire performance of the steel connections.
- Detail design drawings to reflect Architectural, Structural, Mechanical and Electrical components of the building.
- In-depth structural analysis and testing of the proposed design.
- Whole building energy simulation to verify the energy performance and compare the design to a baseline building from the Model National Energy Code (MNECB) or ASHRAE.
- A pilot project scheme with final support available to early adopters of this technology would significantly increase the public exposure and industry knowledge.
- A focused LCA study on the CLT systems should be performed to better quantify the environmental impact.

# APPENDIX A: Athena Summary Measure Tables by Life Cycle Stages

# Summary Measure Table By Life Cycle Stages

**Project** Feasibility Study for 12-Storey Cross Laminated Timber Mixed Used Building - ***Concrete Option***

| | Manufacturing | | | Construction | | | Maintenance | | | End - Of - Life | | | Operating Energy | | Total Effects |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Material | Transportation | Total | Material | Transportation | Total | Material | Transportation | Total | Material | Transportation | Total | Annual | Total | |
| Fossil Fuel Consumption MJ | 49273894 | 2090993.896 | **51364888** | 2103528.7 | 2685680.587 | **4789209** | 8093329.2 | 632256.3484 | **8725586** | 1548565.2 | 1074787.879 | **2623353** | 0 | **0** | **67503036.16** |
| Weighted Resource Use kg | 36216216 | 49167.17676 | **36265383** | 49111.375 | 63210.95378 | **112322.3** | 1090741 | 14894.81499 | **1105636** | 36462.96 | 25324.50244 | **61787.46** | 0 | **0** | **37545128.42** |
| Global Warming Potential (kg CO2 eq) | 5136166.5 | 142135.2765 | **5278302** | 143278.9 | 187388.1947 | **330667.1** | 932379.03 | 46954.97662 | **979334** | 100952.8 | 80455.51303 | **181408.3** | 0 | **0** | **6769711.186** |
| Acidification Potential (moles of H+ eq) | 1770330.4 | 47856.87977 | **1818187** | 66055.059 | 62666.9424 | **128722** | 464084.78 | 14888.67419 | **478973.5** | 5597.02 | 25375.19232 | **30972.21** | 0 | **0** | **2456854.947** |
| HH Respiratory Effects Potential (kg PM2.5 eq) | 17511.041 | 57.66848649 | **17568.71** | 75.416384 | 75.49553448 | **150.9119** | 11118.8 | 17.89690845 | **11136.7** | 5.3282744 | 30.49527545 | **35.82355** | 0 | **0** | **28892.14258** |
| Eutrophication Potential (kg N eq) | 1988.1549 | 49.78423554 | **2037.939** | 64.93624 | 65.16660204 | **130.1028** | 295.23602 | 15.42862034 | **310.6646** | 3.8430764 | 23.97278217 | **27.81586** | 0 | **0** | **2506.522469** |
| Ozone Depletion Potential (kg CFC-11 eq) | 0.0125509 | 5.85166E-06 | **0.012557** | 2.665E-10 | 7.68713E-06 | **7.69E-06** | 0.0003102 | 1.92393E-06 | **0.000312** | 4.548E-06 | 3.29525E-06 | **7.84E-06** | 0 | **0** | **0.012884405** |
| Smog Potential (kg NOx eq) | 12272.597 | 1077.3438 | **13349.94** | 1623.1594 | 1407.041517 | **3030.201** | 5865.3248 | 332.5466678 | **6197.871** | 71.919382 | 566.3613299 | **638.2807** | 0 | **0** | **23216.29398** |

# Summary Measure Table By Life Cycle Stages

**Project** Feasibility Study for 12-Storey Cross Laminated Timber Mixed Used Building - ***CLT Option***

| | Manufacturing | | | Construction | | | Maintenance | | | End - Of - Life | | | Operating Energy | | Total Effects |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Material | Transportation | Total | Material | Transportation | Total | Material | Transportation | Total | Material | Transportation | Total | Annual | Total | |
| Fossil Fuel Consumption MJ | 50309131 | 1295412.388 | **51604543** | 344.44194 | 1746111.148 | **1746456** | 4046753.9 | 602387.3071 | **4649141** | 3764353.9 | 110792.3393 | **3875146** | 0 | **0** | **61875286.12** |
| Weighted Resource Use kg | 15619057 | 30454.36566 | **15649511** | 19.000619 | 40917.5843 | **40936.58** | 930517.8 | 14191.28417 | **944709.1** | 88636.557 | 2610.525224 | **91247.08** | 0 | **0** | **16726404.19** |
| Global Warming Potential (kg CO2 eq) | 3052614 | 87253.41103 | **3139867** | 53.879091 | 86803.67163 | **86857.55** | 753743.7 | 44754.93936 | **798498.6** | 245402.7 | 8293.594186 | **253696.3** | 0 | **0** | **4278919.854** |
| Acidification Potential (moles of H+ eq) | 1521934.4 | 29563.50174 | **1551498** | 27.192948 | 38842.21632 | **38869.41** | 388126.16 | 14187.24971 | **402313.4** | 13605.604 | 2615.750488 | **16221.35** | 0 | **0** | **2008902.091** |
| HH Respiratory Effects Potential (kg PM2.5 eq) | 11700.739 | 35.63350453 | **11736.37** | 0.063291 | 47.27108293 | **47.33437** | 10194.805 | 17.05356703 | **10211.86** | 12.952319 | 3.143543925 | **16.09586** | 0 | **0** | **22011.66103** |
| Eutrophication Potential (kg N eq) | 1111.3194 | 30.76612608 | **1142.085** | 0.005618 | 41.04071839 | **41.04634** | 225.34549 | 14.70149513 | **240.047** | 9.3420022 | 2.471185869 | **11.81319** | 0 | **0** | **1434.991989** |
| Ozone Depletion Potential (kg CFC-11 eq) | 0.0028731 | 3.59406E-06 | **0.002877** | 8.275E-12 | 3.59444E-06 | **3.59E-06** | 0.0002665 | 1.83374E-06 | **0.000268** | 1.106E-05 | 3.39684E-07 | **1.14E-05** | 0 | **0** | **0.003160036** |
| Smog Potential (kg NOx eq) | 8773.6774 | 666.0567848 | **9439.734** | 0.1263788 | 893.7762265 | **893.9026** | 4027.7495 | 316.8682777 | **4344.618** | 174.82635 | 58.38221467 | **233.2086** | 0 | **0** | **14911.4631** |

# APPENDIX B: CLT Systems Background Information