# A COMPARATIVE LIFE CYCLE ASSESSMENT OF MID-RISE OFFICE BUILDING CONSTRUCTION ALTERNATIVES: LAMINATED TIMBER OR REINFORCED CONCRETE

by

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## ABSTRACT

The objective of this project aimed to quantify and compare the environmental impacts associated with the construction of a mid-rise office building. Two alternative scenarios were considered; a traditional cast-in-place, reinforced concrete frame and a laminated timber hybrid design, which utilized engineered wood products including glulam and cross-laminated timber (CLT). The study boundary was cradle-to-gate and encompassed the structural support system and the building enclosure.

A case study building; Discovery Place – Building 12, was selected to represent a typical five-storey office building constructed in North America. Floor plans, elevations, material quantities and design loads associated with the concrete-framed building design were obtained from issued-for-construction engineering drawings. A functionally equivalent, laminated timber design was then conceived, based on the requirements outlined in CAN/CSA-O86-01. Design values for locally produced CLT panels were established from in-house material testing results. A life cycle assessment of CLT, manufactured in British Columbia with mountain pine beetle killed wood, was developed based on primary inventory data collected from a pilot-scale manufacturing facility. Life cycle inventory and impact assessment data for building materials was obtained from secondary sources including BEES<sup>®</sup> 4.0, ATHENA<sup>®</sup> EcoCalculator, CORRIM, and the US LCI. TRACI, an impact assessment characterization methodology, was employed to translate inventory flows into environmental impact indicators.

The environmental comparison of building design alternatives was based on 11 impact categories. The results concluded that the laminated timber building design was associated with a lower environmental footprint in 10 of 11 categories. At a minimum, the heavy timber design demonstrated a 14% improvement, when considering acidification potential. At a maximum, the timber design exhibited a global warming potential that was 71% less than the concrete design. Fossil fuel depletion was the only category where the concrete design was superior, displaying a 6% advantage over the timber scenario. The cumulative embodied energy of construction materials was also calculated; with results estimating energy contents of 116 and 66 terajoules for the timber and concrete designs, respectively. The concrete building acquired 20% of its energy from renewable sources, whereas in the timber-framed case, renewables accounted for over 60% of the combined feedstock and process energy.

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# LIST OF ABBREVIATIONS, SYMBOLS AND ACRONYMS

~.	Approximately	
<u> </u>		
	Also known as	
ASMI:	ATHENA <sup>®</sup> Sustainable Materials Institute	
ASTM:	American Society for Testing and Materials	
B.C.:	British Columbia	
BCBC:	British Columbia Building Code	
BEES <sup>®</sup> 4.0:	Building for Environmental and Economic Sustainability	
ccSPF:	Closed cell spray polyurethane foam	
CIRS:	Centre for Interactive Research on Sustainability	
CLT:	Cross-laminated timber	
cm:	Centimetre	
cm <sup>2</sup> :	Square centimetre	
CNC:	Computer numerical controlled	
CO <sub>2</sub> :	Carbon dioxide	
CORRIM:	Consortium for Research on Renewable Industrial	
	Materials	
Criteria air pollutants:	Air pollutants regulated to permissible levels by the	
	USEPA, based on human health criteria; O <sub>3</sub> , CO, SO <sub>2</sub> , Pb,	
	NO <sub>x</sub> and total suspended particulates are the criteria	
	pollutants (Bare et al., 2003)	
CSA:	Canadian Standards Association	
D.Fir-L:	Douglas Fir-Larch	
DL:	Dead load	
e.g.:	For example	
Eco-toxicity:	Ecological toxicity	
EE:	Embodied energy	
EIO:	Economic input-output	
eq.:	Equivalents	
et al.:	And others	
etc.:	Et cetera	
EU:	European Union	
EWP:	Engineered wood product	
f'c:	Compressive strength	

ft:	Feet
ft <sup>2</sup> :	Square feet
ft <sup>3</sup> :	Cubic feet
G:	Ground floor
GHG:	Greenhouse gas
GJ:	Gigajoule
Glulam:	Glued-laminated timber
GWP:	Global warming potential
HP:	Horsepower
i.e.:	That is; in other words
ICI:	Industrial, commercial, institutional
in:	Inch
in <sup>2</sup> :	Square inch
incl.:	Included
ISO:	International Standards Organization
J:	Joule
K:	Kelvin
kg:	Kilogram
kJ:	Kilojoule
kN:	Kilonewton
kPa:	Kilopascal
kW:	Kilowatt
lbs:	Pounds
LCA:	Life cycle assessment
LCI:	Life cycle inventory
LCIA:	Life cycle impact assessment
LEED <sup>®</sup> :	Leadership in Energy and Environmental Design
LL:	Live load
LLRF:	Live load reduction factor
Ltd.:	Limited
μm:	Micrometre
mm:	Millimetre
m:	Metre
$m^2$ :	Square metre
$m^3$ :	Cubic metre

MJ:	Megajoule
MOE:	Modulus of elasticity
MPa:	Megapascal
MPB:	Mountain pine beetle
MUF:	Melamine urea formaldehyde
N:	Newton
NBCC:	National Building Code of Canada
NO <sub>x</sub> :	Nitrogen oxides
O/C:	On-centre
OECD:	Organisation for Economic Co-operation and Development
OSB:	Oriented strand board
PM <sub>10</sub> :	Particulate matter less than 10 µm in diameter
PRF:	Phenol resorcinol formaldehyde
PU:	Polyurethane
R:	Ductility-related force modification factor
RSI:	Heat resistance (m <sup>2</sup> K/W)
S/W:	Self-weight
SBS:	Styrene-butadiene-styrene
SCM:	Supplementary cementing material
SDL:	Superimposed dead load
SO <sub>2</sub> :	Sulphur dioxide
S-P:	Spruce-Lodgepole Pine-Jack Pine
TJ:	Terajoule
TRACI:	Tool for the Reduction and Assessment of Chemical and other Environmental Impacts
U.K.:	United Kingdom
U.S.:	United States of America
U/S:	Underside
UBC:	University of British Columbia
UDL:	Uniformly distributed load
US LCI:	United States Life Cycle Inventory Database
USEPA:	United States Environmental Protection Agency
vs.:	Versus
W:	Watt
yd:	Yard

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> Adam B. Robertson - Vancouver, 2010

# DEDICATION

To our future generations -

Whom all deserve to inherit a healthy planet.

## **1.0 – INTRODUCTION**

### 1.1 – Project Motivations

#### 1.1.1 – Environmental Sustainability

The construction and operation of buildings are responsible for the consumption of up to 40% of global energy use, as well, at least one third of the anthropogenic greenhouse gas (GHG) emissions in developed and developing countries can be related to activities in the building and construction sectors of the economy (UNEP, 2009). During 1990 to 2005, Canada experienced a 17% population growth; however, the primary energy use increased by 27%, with the commercial and institutional buildings sector being the fourth largest GHG emitter (Natural Resources Canada, 2009). Energy and resource conservation, along with environmental sustainability are issues at the forefront of governments, business, and academia worldwide. Finding measures to mitigate the environmental impact of buildings throughout their life cycles is a topic that is being discussed by both developed and developing countries around the world. Improving the environmental and energy use performance of the world's building sector, using proven and commercially available technologies, is an initiative often toted as one that has the potential to offer the highest environmental returns for the lowest economic investment (UNEP, 2009). Energy and resource consumption for building production and operation, along with associated GHG and other harmful environmental emissions demonstrate that there exists a link between building life cycles (raw materials acquisition, manufacturing, construction, operation, and end-of-life choices), the natural environment, and climate change.

The world's population is expanding; in the future we will need more buildings for society to live and work. Taking the time and effort to analyze, quantify, interpret, and compare the environmental impact that contemporary building design alternatives afflict on the natural environment, including their role in contributing to global climate change and environmental degradation is a primary motivation behind this research.

#### 1.1.2 – Mountain Pine Beetle

Presently, the Pacific Northwest and British Columbia in particular, are suffering from the worst mountain pine beetle (MPB) outbreak in recorded North American history. This ecosystem altering epidemic is causing widespread mortality of the lodgepole pine forests, the most abundant commercial tree species in British Columbia. The MPB has infected over 70% of the lodgepole pine trees in the province (International Wood Markets Group Inc., 2010), with more than 50% of the province's mature lodgepole pine having already been killed (Gilbert, 2010). The bark beetle has also migrated south into the northwest United States, east into Alberta and is posing a significant threat to the jack pine stands of Canada's northern boreal forest (Natural Resources Canada, 2010).

The MPB is a naturally occurring species in the Pacific Northwest that was traditionally kept under control by prolonged periods of cold winter temperatures. MPB targets only a small array of tree species, with the most commonly attacked species being mature lodgepole pine. After initial infestation, the blue stain fungi that the MPB carries acts to decrease the moisture content of the tree, turning the leaves from a healthy green to a dark, rusty red colour, with the grey stage of the attack preceding tree death (Safranyik & Carroll, 2006).

Due to the severity of the current MPB attack, there is a surplus of infected, unused lodgepole pine and standing dead wood throughout the province. The volume of MPB attacked trees is enormous; approximately 620 million cubic metres or an area four times the size of Vancouver Island (Hamilton, 2009), with the MPB epidemic expected to kill one billion cubic meters of B.C. timber before it subsides (Hamilton, 2010). If this wood fibre is not converted into a useable product, such as dimensional lumber or biofuel, it will eventually decay and release carbon dioxide ( $CO_2$ ) into the atmosphere. Over the last five years, the excessive volume of rotting dead fall, resulting from MPB killed timber has resulted in British Columbia's forests becoming net emitters of  $CO_2$ (Ministry of Environment, 2009).

Finding feasible, economically viable, and environmentally responsible solutions to mitigate the effect of the MPB epidemic is at the forefront of government policy and academic research. The Government of B.C. has proposed solutions for the use of MPB

infected lumber; with innovative, value-added, engineered wood products (EWPs) being a primary focal point for research, development, and implementation in the nonresidential building market (Forestry Innovation Investment Ltd., 2010).

#### 1.1.3 – Provincial Building Code Changes

On April 6<sup>th</sup> of 2009, the Government of British Columbia amended the B.C. Building Code (BCBC) to permit the design and construction of wood-framed buildings up to six-storeys in height (Government of British Columbia, 2009). The previous height restriction for wood-frame structures was four storeys. This change signifies the government's desire to encourage the application of wood and timber construction techniques in the mid-rise building sector. In North America, the mid-rise, nonresidential building sector is currently dominated by the use of reinforced concrete and wide flange steel as the primary structural support systems (Slaco, 2008). The advancement in understanding of timber building behaviour, along with the refinement of EWP design and performance has demonstrated the applicability of using wood as a primary structural support mechanism in mid-rise building construction.

With the introduction of taller wood-framed structures, several design implications were considered by the building code officials before the amendments to the building code were approved. Fire safety, structural design practices, building envelope, serviceability, and educational outreach considerations were all addressed in comprehensive reports issued by the Government of British Columbia and the Association of Professional Engineers and Geoscientists of British Columbia (Skulsky, 2008; Harmsworth et al., 2008; Harmsworth & Chen, 2009; APEGBC, 2009). The overarching conclusions offered by these studies were that six storey wood-framed construction is a safe and viable alternative to either reinforced concrete or wide flange steel with respect to structural, fire safety, and serviceability performance criteria.

This research project uses the building code changes as an impetus for examining the environmental impact of different mid-rise building construction scenarios.

#### 1.1.4 – British Columbia Wood First Act

In late September of 2009, the province of British Columbia introduced the Wood First Act, with the legislation receiving Royal Assent into Provincial law on October 29th of the same year (Ministry of Forests and Range, 2009). "The Wood First Act aims to increase demand for wood products by requiring provincially-funded projects to use wood as the primary building material, generating new demand for wood, stimulating the province's forest industry, and securing long-term markets to ensure a sustainable wood industry" (Wood WORKS! BC, 2010, p. 30). The provincial government believes that wood is under-utilized in the non-residential building sector, accounting for only 19% of the commercial and institutional building market (Ministry of Forests and Range, 2009). The implementation of the Wood First Act in this province has acted as a catalyst and spurred interest and a following by municipal, regional, and federal government bodies across Canada. To date, 13 B.C. communities, including the cities of Quesnel, Kelowna, and Squamish have all adopted a wood first standard for their municipally funded projects (Wood WORKS! BC, 2010, p. 30). The first reading of Bill C-429 took place in June, 2010, before the federal House of Commons and if passed, has the potential to give preference to project bidders that use wood products in the construction of federally funded buildings (Moneo, 2010).

Presently, there are concerted efforts being made throughout Canadian government bodies to promote the use of domestic timber and wood construction systems in publicly funded buildings. The Wood First Act aims to increase demand for wood products within B.C. and is an attempt to help revive the forestry and timber building products industries that were wounded during the recent economic downturn. The provincial government of B.C. is also attempting to showcase wood construction as an economically and environmentally advantageous building solution, with aims of achieving long term sustainability goals (Ministry of Forests and Range, 2009).

The Wood First Act has provided motivation to obtain additional quantitative figures about the advantages and disadvantages of wood building construction. This calculated information has the potential to aid government officials, designers, and builders, in making informed choices regarding the environmental impacts of construction material selection and building design.

## 1.2 – Research Question

The research question that has been derived for this project is multifaceted and stems from the environmental and bureaucratic motivations that were discussed in the previous sections. The first, broad based question, was that of environmental sustainability with respect to building design and construction. What alternative building design and construction scenarios are more environmentally advantageous? This question is wide in scope and was narrowed down, based on the B.C. Building Code changes and the Wood First provincial legislation that took place in 2009. Now that timber-framed construction is permitted in buildings up to six-storeys in height and mandated in all provincially funded projects, the question of material substitution for environmental reasons was raised. The first iteration of the research question was tailored to address both the Wood First initiative and the building code change; what are the environmental advantages or disadvantages of constructing a mid-rise building using timber instead of traditional building materials such as, concrete, steel or masonry?

The MPB epidemic in the Pacific Northwest led to the inclusion of a research focus on the environmental merit and feasibility of using MPB infected timber for innovative EWP that could be used in mid-rise building construction. Cross-laminated timber (CLT), a relatively new EWP that is being introduced in North America and glued laminated timber (glulam) surfaced as solutions that had the ability to utilize large volumes of MPB killed timber in non-residential applications and presented a substitute for traditional structural systems in the mid-rise (4–6 storey) building sector. The ultimate research question was refined to; what are the comparative environmental impacts of a mid-rise, non-residential building, located in British Columbia, which uses (a) cast-in-place reinforced concrete exclusively; or (b) a hybrid concrete and laminated timber (CLT and glulam) frame as the primary structural support system?

## 1.3 – Research Objectives

There are two main objectives to this research project:

- Develop an environmental impact comparison of a mid-rise concrete-framed building and a functionally equivalent timber-framed building, located in British Columbia's Lower Mainland region.
- Calculate and interpret the structural and environmental performance profiles of cross-laminated timber; incorporating this information in the timber building design scenario and the environmental impact analysis comparison.

This research uses the life cycle assessment technique to demonstrate the comparative environmental differences between alternative building design and construction scenarios; in hopes of providing valuable scientific information and guidance to designers, developers, and government decision makers on the environmental impacts of competing construction techniques. This projects aims to synthesize environmental concerns (sustainability, MPB attack) and bureaucratic mandates (Wood First Act, B.C. Building Code amendments), in order to quantify and compare the environmental impacts, design, and constructability issues related to reinforced concrete and heavy timber building systems.

#### 1.4 – Literature Review

The existing literature on comparative life cycle assessment (LCA) of alternative construction systems and building products has been developed in several OECD nations around the world, including the European Union (EU), the United Kingdom, Japan, Australia, New Zealand, the United States, and Canada. The interest in applying environmental impact evaluation techniques to building design seems to have surfaced in the late 1980s and become a more popular and active research area in the last decade. Due to the spatial and temporal sensitivity of LCA, the literature review will focus on studies that have concentrated on the mid-rise, industrial, commercial, and institutional

(ICI) building sector and that have taken a North American approach to building design, materials production, and construction practices.

The first LCA study that compared the environmental impact of alternative structural assembly systems was published by Marcea & Lau (1992). This Canadian research project evaluated the embodied energy and  $CO_2$  emissions associated with the construction of the 11,000 m<sup>2</sup> Forintek Western research facility in Vancouver, British Columbia, constructed as either a wood or steel-framed structure. The data for this study was based on 1981 United States Department of Energy statistics and included energy requirements and  $CO_2$  emissions associated with the raw materials extraction, manufacturing, on-site erection, and maintenance for the supporting structure, over a 50-year life span. The results of the Marcea & Lau (1992) study concluded that the embodied energy was 0.74 and 2.08 GJ/m<sup>2</sup> of gross floor area, for the wood and steel alternatives, respectively, and the  $CO_2$  emissions associated with the wood and steel design scenarios was 448 and 1,396 tonnes, respectively.

In the following few years, an interrelated set of LCA studies pertaining to alternative office building construction scenarios in Canada were produced by Cole (1994) and Cole & Kernan (1996). These projects compared the life cycle environmental impacts of a three-storey, 4,645 m<sup>2</sup> (50,000 ft<sup>2</sup>) office building, with and without underground parking, located in Vancouver and Toronto. The structural systems under comparison were reinforced concrete, structural steel and wood framing. In both studies, a similar conclusion was reached; the wood-framed design had the lowest embodied energy of construction materials. The findings of the Cole & Kernan (1996) study concluded that the wood-framed building had the lowest embodied energy of construction materials at 4.54 GJ/m<sup>2</sup>, followed by the concrete frame with 4.79 GJ/m<sup>2</sup> and lastly the steel framed building at 5.13 GJ/m<sup>2</sup>, when considering a design with one level of underground parking. Another valuable conclusion of this work found that the embodied energy of the building materials accounted for 20–30% of the total life cycle energy requirement and could rise to as much as 45% by increasing the operating energy efficiency characteristics, based on a 25- to 100-year building lifetime.

A project of similar scope was conducted by the CWC (1997), which retained engineers to develop alternative structural design configurations for a  $4,620 \text{ m}^2$ , three-

storey office building with one level of underground parking, using either wood, steel or concrete for the above-grade structure. The results of the CWC (1997) study indicated the wood-framed design had the lowest total energy use, GHG, air, and water pollution indexes, as well as the least amount of solid waste and associated ecological resource use.

The estimates made by Cole & Kernan (1996) related to the increased percentage of embodied energy associated with higher operating efficiency over the building use phase were confirmed by Thormark (2002) whom studied the most energy efficient Swedish apartment housing constructed in the year 2000. This study found embodied energy accounted for 40% of total energy need over the life cycle, when considering a 50-year building life span. The rising importance of embodied energy, when considering high performance building designs was echoed in a literature review that analyzed 60 building cases throughout nine countries and considered the relationship between operating energy and embodied energy. Sartori & Hestnes (2007, p. 249) remarked that the "design of low-energy buildings induce both a net benefit in total life cycle energy demand and an increase in embodied energy".

The relative rise in the embodied energy associated with construction materials of high performance buildings was recently verified by a LCA study at Rutgers University. Krogmann et al. (2008; 2009) calculated that the materials placement phase (raw material extraction and manufacturing) contributed 41% to the total life cycle primary energy consumption when examining a new 891 m<sup>2</sup>, green educational building in the United States. When taking into account the global warming and acidification potentials of the newly constructed university building, the authors also found a similar increase in the relative importance of the materials placement phase with respect to the operating phase (Krogmann et al., 2008; 2009). This study has alluded to the notion that with the succession from conventional to more energy efficient building design, material choices become increasingly relevant towards minimizing environmental impacts, as they will have a larger share of the environmental burden over the life cycle than they did in the past.

A master's thesis, conceived at the University of British Columbia by Hood (1995), built on the work by Cole (1994); using the same floor plate but increasing the building height by two-storeys. This thesis project investigated the embodied energy of a

typical five-storey, reinforced concrete-framed office building located in Vancouver, British Columbia. This project used a combination of building material life cycle assessment methods; including economic input-output (EIO), process-based, and national statistical databases. In 1995, at the time of publication, there was no North American specific building material life cycle inventory (LCI) database and therefore LCA results for this study were generated from building material production data in New Zealand, the United Kingdom, and Japan. The conclusion of the research by Hood (1995) was that the embodied energy of the five-storey concrete-framed office building, including one level of underground parking, was 4.26 GJ/m<sup>2</sup>.

A second iteration of the five-storey concrete-framed office building analysis was performed by Kernan (1996). The University of British Columbia thesis calculated the embodied energy of the building materials to be equal to  $4.03 \text{ GJ/m}^2$  of gross floor area. Similar to the previous two studies by both Cole and Hood, the building design included one level of underground parking with standard bay sizes of 7.5 meters square in plan.

Guggemos & Horvath (2005) performed a comparative LCA of a typical office building constructed with either a cast-in-place concrete or structural steel frame, located in the Midwestern United States. The case study building was five-storeys in height, with no underground parking, having a gross floor area of 4,400 m<sup>2</sup> and a design lifetime of 50 years. This study used a hybrid model of both process-based and EIO data for the year 1997 to compute the environmental impact indicators. Guggemos & Horvath (2005, p. 98) concluded that when considering only the materials, construction, and end-of-life phases, "the differences in environmental effects due to the two frame types are not prominent".

In 2006, Junnila et al. published a study that compared the relative environmental performance of two similar office buildings, one located in southern Finland and the other in the Midwestern United States. Both structures were supported by reinforced concrete frames and had the same gross floor area (4,400 m<sup>2</sup>), despite the Finnish building consisting of four-storeys and the American counterpart having five. With respect to the non-use phases (materials production, construction, maintenance, and end-of-life), the Finnish building outperformed its American counterpart in all five evaluation categories (embodied energy,  $CO_2$ ,  $SO_2$ ,  $NO_x$ , and  $PM_{10}$ ) by a minimum of 60%. When

compared over each building's lifetime, the relative environmental impacts at each of the life cycle phases were similar for both geographical regions. Finally, Junnila et al. (2006, p. 16) concluded that a 50-year building lifespan may be an overestimate given that "there is a recent trend on both sides of the Atlantic to completely reconstruct and reconfigure office buildings from the 1960s...therefore, the relevance of the nonuse phases, i.e., the materials, construction, maintenance, and end-of-life stages relative to the use phase of buildings is expected to increase as functional obsolescence of office buildings becomes more rapid, and complete reconstruction and reconfiguration become more frequent."

An article published by Ortiz et al. (2009, p. 33) stated that "there has been a fair amount of descriptive work on commercial constructions, but limited research has been published thus far on complete LCA of office buildings". Based on the literature review, there exists no studies on the environmental impacts of mid-rise commercial office buildings, located in Canada or anywhere else in the world, that compares heavy timber laminated EWP (glulam and CLT) and cast-in-place reinforced concrete construction systems. This present research thesis strives to develop, assemble, and combine the existing aggregated life cycle data available for different building products and construction systems in order to compare functionally equivalent timber and concrete building design alternatives.

## 2.0 – METHODOLOGICAL FRAMEWORK

### 2.1 – Case Study Building

Discovery Place – Building 12 was selected as the case study example, because of its design, use, location, and construction system. Discovery Place is a 14,233 m<sup>2</sup> office building, located in Burnaby, British Columbia, at 4200 Canada Way. The building is situated among a cluster of other similar use buildings; in a commercial park that was established for high-tech research companies. Discovery Place was a desirable candidate for this research project because the building fit in with several of the project motivations. During design and construction, this mid-rise office structure was touted as being at the leading edge of building environmental stewardship, "raising the bar for sustainable commercial buildings" (Mah, 2009, p. 10) and early in 2010, Discovery Place - Building 12 was awarded the platinum certification level, the maximum score under the LEED<sup>®</sup> Canada Core and Shell rating system. The occupancy and use of the building was a factor in its selection; examination of a building in the non-residential sector was imperative. The Government of B.C., through the Wood First Act, gives precedence to wood as the primary building material in publically funded projects that could conceivably be similar in size and use to Discovery Place – Building 12. The case study building's location, in the Lower Mainland of British Columbia, was also relevant in the selection process. The geographical proximity ensured the validity of region specific environmental impact data. Finally, the building height of five-storeys correlated with the amendments made to the BCBC, which now allow for wood-frame construction to be built to a maximum height of six-storeys. The designer's decision to use reinforced concrete as the structural frame was also perceived as typical industry practice for a building of this height and use. An architectural rendering of Discovery Place – Building 12 is shown as Figure 1.



Figure 1 – Discovery Place - Building 12 (Bunting Coady Architects, 2007)

The LCA comparison of alternative design scenarios for Discovery Place – Building 12 was tailored to be focused on two main systems; the primary structural support systems (cast-in-place reinforced concrete or glulam/CLT) and the building enclosure or envelope system. The reason behind confining the environmental analysis to these two building systems was for minimization of inventory calculation data, as well as focusing on the two building elements that are responsible for 60 to 90% of the total embodied environmental impacts of commercial office buildings (Junnila, 2004; Oritz et al., 2009).

### 2.1.1 – Concrete Structural System

The structural support system for Discovery Place – Building 12 was designed and constructed in a manner that is considered the industry norm for buildings of this size and use. All structural design information was obtained from the issued-for-construction structural engineering drawings, produced by Reid, Jones, Christoffersen (RJC) Consulting Engineers (2007). The foundation consisted of concrete spread footings, overlaid by a 102 mm (4 in) slab-on-grade. There were three levels of underground parking, extending 8.84 m (29 ft) below the ground floor level. The underground parking levels were framed with concrete foundation walls and interior concrete columns that supported cast-in-place reinforced concrete slabs. The underground parking slab ranged in thickness from 165 to 241 mm (6.5 to 9.5 in), increasing to 406 mm (16 in) at the slab band locations, with the exterior foundation walls having a thickness of either 254 or 305 mm (10 or 12 in).

At the ground floor level, the building footprint dand the column layout was altered. A portion of the ground floor included a double height atrium space. All floors, from the ground to the 5<sup>th</sup> were vertically supported by cast-in-place reinforced concrete slabs and columns. The common slab thickness from the  $2^{nd}$  floor to the roof was 229 mm (9 in) and the columns ranged in size from 1,652 to 6,194 cm<sup>2</sup> (256 to 960 in<sup>2</sup>). Spandrel edge beams were employed to support the vertical and horizontal loading of the double glazed curtain wall system. These edge beams range in depth from 686 to 1,524 mm (27 to 60 in).

With respect to the lateral force resisting system of the Discovery Place building; a series of shear walls and shear cores were utilized. There was one main elevator core, located centrally, close to the shear centre of the building, which was used as both a torsional and lateral force resistance system. There also existed two stair cores that were located on west and south wings of the building, which provided lateral and torsional force resistance. The concrete floor slabs were considered as a shear diaphragm system that transferred horizontal loads to the surrounding columns and shear walls. The columns themselves had the ability to resist lateral forces, so called beam-columns, but it was not known if the above grade columns were designed as moment resisting beamcolumns, or solely as vertical force resisting members.

#### 2.1.2 – Exterior Building Enclosure

The building enclosure (also known as the building envelope) of Discovery Place – Building 12 consisted of three different weather and wind resisting elements; a built-up exterior wall assembly, a curtain wall system (visual glazing and thermally insulated

spandrel glazing elements), and a built-up roofing system, as well as operable openings such as pedestrian and vehicular access doors. Although the building enclosure also consisted of a below-grade foundation wall system, this description will focus only on the above-grade building envelope. The purpose of the envelope is multi-faceted, although "the primary function of the building enclosure is to separate the interior environment from the exterior environment to which it is exposed" (Straube, 2006, p. 3). The building enclosure is used as a barrier to heat, sound, moisture ingress, and air movement, as well as acting as a mechanism to transfer horizontal and vertical forces. The following information regarding the make-up of the building envelope assembly was obtained from the issued-for-construction drawings, prepared by Bunting Coady Architects (2007).

Beginning from the top of the building, the roof waterproofing assembly of Discovery Place – Building 12 consisted of a 2-ply SBS membrane, made of a modified bituminous compound. This waterproofing layer can be torch applied or mechanically fastened to the 229 mm (9 in) concrete slab and was topped with gravel and concrete pavers where pedestrian traffic was anticipated. Overlaid on the bituminous membrane, there was a 76 mm (3 in) layer of R-12 rigid insulation (expanded/extruded polystyrene). Atop the rigid insulation, laid a 6 mm polyethylene vapour barrier. On the underside of the concrete slab, inside the building, a 64 mm (2-1/2 in) thick R-12 closed cell spray polyurethane foam (ccSPF) was applied to only four feet of the roof slab that extended inwards from the building edge. In other words, 11.25% of the roof slab was underlain with 64 mm (2-1/2 in) thick ccSPF. The average RSI value of the entire roofing assembly was 2.68 m<sup>2</sup>K/W and the total thickness was approximately 380 millimetres (see APPENDIX B – Building Envelope Design for calculations).

Beginning from the outside, the exterior wall make-up of the Discovery Place building consisted of a 203 mm (8 in) concrete wall that was exposed to the outdoor environment. Moving inwards, there was a 13 mm ( $\frac{1}{2}$  in) air space with 92 mm ( $3-\frac{5}{8}$  in) steel studs at 406 mm (16 in) on-centre. Sprayed over the concrete wall and the steel studs were 64 mm ( $2-\frac{1}{2}$  in) of ccSPF that acted as insulation and a vapour barrier. The wall assembly was finished with 13mm ( $\frac{1}{2}$  in) gypsum wall board, screwed to the studs. The exterior wall assembly had a total thickness of 321 millimetres, with an averaged

RSI value of 1.58  $m^{2}$ K/W (see APPENDIX B – Building Envelope Design for calculations).

In conjunction with the opaque wall assembly, Discovery Place also contained a curtain wall system that had both transparent visual glazing and insulating spandrel elements. The curtain wall system is physically separated from the concrete structure by way of an aluminum mullion system. The visual section of the curtain wall is made up of double glazed, thermally broken vision panels, whereas the spandrel was a single glazed element with a metal back panel that acted as an air and vapour barrier. Integral to the spandrel back panel was 25 mm (1 in) R-12 semi-rigid insulation, 92 mm (3-5/8 in) steel studs at 610 mm (24 in) on-centre and finished with 13 mm (1/2 in) gypsum wall board. The overall curtain wall assembly consisted of approximately 70% vision glass and 30% spandrel paneling, with an average overall U-value of 0.722 W/m<sup>2</sup>K (see APPENDIX B – Building Envelope Design for calculations).

## 2.2 – Timber Building Redesign

In order to perform an environmental comparison of two alternative construction scenarios for Discovery Place – Building 12, it was necessary to redesign the case study concrete-framed building using timber elements. The goal was not to perform a direct material replacement or substitution, but to redesign a functionally equivalent structural system and building envelope, by choosing EWP and dimensional lumber where a feasible option existed. In almost all instances, the footprints, floor-to-floor heights, and overall building dimensions in both design scenarios were the same or varied by only a few centimetres. In order to facilitate the redesign, it was first necessary to understand the performance characteristics of the concrete-framed building, as outlined in the previous section, so that an equivalent timber counterpart could be developed.

Several design considerations were taken into account when redesigning the timber version of Discovery Place – Building 12. The following sections outline the structural timber material's properties and performance, as well as the timber building design criteria and decisions. The design topics that are discussed include: feasibility of

mid-rise heavy timber-framed construction, CLT and glulam performance and structural design applications, gravity loading, lateral loading, and envelope design.

### 2.2.1 – Feasibility of Mid-Rise, MPB-killed, Heavy Timber Construction

At the time this study was conducted, the concept of designing and constructing large footprint, mid-rise office buildings, using heavy timber and CLT structural frames was not typical industry practice in British Columbia. The redesign of Discovery Place – Building 12, using a combination of glulam and CLT for the vertical and horizontal force resisting systems was considered a feasible solution based on the constructed examples that existed in both Canada and throughout the European Union.

At the present time, there were only a few prominent examples of mid-rise, heavy timber construction that existed in Canada. The first and most closely related to the design of Discovery Place – Building 12 was the Fond-action building in Quebec City, Quebec. This six-storey commercial structure provided the first Canadian example of the viability of mid-rise, heavy timber office building construction. This structure was built using black spruce glulam beams, columns, and decking (Frappier, 2010). The Fondaction building also showcased the ability of heavy timber framed structures to meet National Building Code of Canada and provincial code requirements in a jurisdiction that did not explicitly allow combustible timber-framed construction above four-storeys in height. There are also two examples of heavy timber design at the University of British Columbia; the Centre for Interactive Research on Sustainability (CIRS) and the UBC Bioenergy Research and Demonstration Project, that both demonstrate the feasibility of heavy timber-framed building construction. Under construction at the time of publication, the CIRS building utilized an above-grade heavy timber glulam frame built over a concrete foundation, with the lateral racking system of the building being concrete cores and shear walls to account for wind and seismic design considerations. The design of this four-storey glulam-framed building, with concrete elevator and stair cores, clearly demonstrated the applicability of combining heavy-timber with concrete cores as a structural solution for mid-rise building designs in the Lower Mainland. Presently in the final design stages, the UBC Bioenergy Research Demonstration Project, slated to be

built on the Vancouver campus, is a pilot plant structure designed using CLT walls and roof plates and is scheduled to be the first North American project built exclusively using provincially-sourced CLT panels (UBC Board of Governors, 2009). The final Canadian construction example that used heavy timer CLT panels occurred in Whistler, B.C., where European-manufactured CLT floor plates, supported by glulam beams and round timber columns were used in the two-storey Austrian Passive House that was erected for the 2010 Winter Olympics. Although the UBC Bioenergy and Austrian Passive House buildings were shorter in height and smaller in footprint than the case study structure, they demonstrated and showcased the perceived applicability and feasibility of heavy timber-framed design and construction using a combination of CLT, glulam and reinforced concrete in a similar geographic, climatic and seismic design zone as Discovery Place – Building 12.

With respect to the design and construction of mid-rise heavy timber-framed buildings in the Europe Union, examples are widespread and plentiful. The flagship example of mid-rise CLT construction is the Stadthaus, a nine-storey, 29 unit apartment building located in London, England, completed in 2009. The Stadthaus was designed using reinforced concrete for the first storey and CLT walls and floors for the remainder of the building, including CLT elevator shafts and stair cores. Currently, the Stadthaus is the tallest residential wood structure in the world (TRADA Technology, 2009). A second prominent example of mid-rise, CLT construction existed in Växjö, Sweden. The Limnologen project is an eight-storey, 33 unit, 3,374 m<sup>2</sup> heavy timber-framed structure (CLT and glulam) that is currently the tallest residential timber structure constructed in Sweden. The structure of the Limnologen consisted of 3-ply CLT floors and exterior walls, with maximum clear spans of 8.5 metres and connections made with steel angle brackets. The CLT floors and walls accounted for approximately 80% of the structure, while the remaining 20% of the building used stud and rail construction, primarily as partition walls (Vessby, 2009). Another recent example of the feasibility of mid-rise heavy timber construction in the ICI sector is the Open Academy, a large, three-storey, 9,000 m<sup>2</sup> school, located in Norwich, England. Many similarities can be drawn from this project and the case study building (Discovery Place – Building 12), including the combined use of glulam beams and CLT floors and walls, as well as the fact that the

Norwich structure utilized the horizontal diaphragm action of the CLT floors and roof plates, using this horizontal shear force transmission system to relay lateral wind loads to the vertical racking walls and shear cores (TRADA Technology, 2010). The Open Academy also showcased the feasibility of using CLT in cantilevered staircases and curved exterior wall and roof applications, aesthetically pleasing concepts that are only recently being realized by CLT designers and manufacturers alike.

The feasibility of mid-rise, heavy timber construction using glulam and CLT can be found in many European projects that were built in the past two decades. Throughout Western and Central Europe, there exist several other constructed examples of both residential and commercial applications of heavy timber-framed, mid-rise structures, which vary widely in gross floor areas and heights. Examples of this type of wood-frame construction are located in other countries besides England and Sweden, most notably Germany, Austria, Switzerland, Italy, Finland, and Norway.

Where at all possible, the timber elements that were used in the redesign of Discovery Place – Building 12 were considered to be manufactured with MPB killed lodgepole pine lumber. This includes structural EWP components such as glulam beams and columns, CLT floors, and walls, as well as the dimensional lumber used in the design of the building enclosure. The impetus behind this decision resulted from the large volume of MPB killed wood that exists in British Columbia and the desire to design and demonstrate solutions that incorporate larger volumes of wood in the building design.

For a designer, the major difference in MPB-killed and uninfected wood lies in the visual aesthetics. The environmental benefit of utilizing salvage harvest MPB-killed trees that would otherwise rot, decay or possibly burn and release  $CO_2$  into the atmosphere versus cutting down of live, healthy trees is outside the scope of this work and was not explicitly quantified in this research project; although the quantity of carbon stored within the timber structure and envelope was taken into consideration.

#### 2.2.2 – Cross-Laminated Timber

Cross-laminated timber (CLT) is an innovative EWP that was developed in central Europe for the low- and mid-rise building construction market. The first

appearance of CLT was in Switzerland in the 1970s (Edinburgh Napier University, 2009), with the initial research and development projects occurring at the Graz University of Technology in Austria in the early 1990s, including work pioneered by Dr. Gerhard Schickhofer. CLT (also known as massive/massif timber panels or XLam) is composed of sawn lumber that is stacked in orthogonally oriented layers. This layup design creates large wood panels that can have varying thicknesses, depending on the number of lamellas or ply layups. The alternating ply layups also cause the plates to have a strong and a weak bending direction. CLT panels are manufactured in odd number ply layups (3, 5, 7, etc.) and range in thickness from 60 to 400 mm (Falk, 2005). The length and width of CLT panels are also variable and typically reach maximum sizes of 3 by 15 metres in plan. In order to be able to manufacture panels of considerable length, individual pieces of dimensional lumber are finger jointed and bonded together at their ends. The lamellas can be held together by different types of fastening systems; including wooden dowels, nails and wood adhesives. In the EU, the most popular type of bonding system is adhesive gluing, over the entire surface area of the lamella faces. Figure 2 shows an experimental CLT panel that was manufactured in British Columbia from MPB-killed lodgepole pine.



Figure 2 – CLT panel, 3-ply system, MPB lodgepole pine (Lam & Chen, 2007, p. 16)

The structural building applications of CLT panels are widespread. They can be used as both vertical and horizontal load-bearing elements such as walls, floors, and roofs. It is also possible to use CLT as an elevator or stair core; utilizing its ability to resist both vertical and lateral loads. According to U.K.-based TRADA Technology (2009), CLT has the structural capability to be used in mid-rise building construction scenarios that reach heights of up to 12 storeys. It is also possible to cut different size and shape openings in the CLT panels, allowing for opportunities in the fenestration where doors, windows, and services (pipes, ducts, etc.) can be installed.

For the timber redesign of Discovery Place – Building 12, CLT was utilized as a replacement for the reinforced concrete floor and roof slabs, along with the exterior loadbearing walls and the double storey columns at the main entrance. Currently, there are no building code-approved design criteria that exist for the structural use of CLT in Canada or the United States. In order to formulate strength and stiffness properties of Canadian manufactured MPB CLT plates, testing data published by Chen (2009; 2011) was referenced. The structural testing data provided ultimate compression parallel to grain stress, ultimate bending stress and modulus of elasticity (MOE) for 30 specimens in compression and three CLT plate specimens in bending. All tested CLT plates were 3ply systems, manufactured from 38 x 89 mm (nominal 2 x 4") B.C. grown, MPB-killed lodgepole pine lumber, No. 2 grade or better. The final panel thickness, after planing, was 99 millimetres, with plan dimensions of 1.079 meters in width by 2.158 meters in span length (Chen et al., 2008, p. 172). The lamellas were face glued together using phenol resorcinol formaldehyde (PRF) glue, while finger jointing of the dimensional lumber was not employed. The calculated design values for bending and compression parallel to grain were based on the 5<sup>th</sup> percentile ultimate strength, with a 75% confidence interval, as specified in ASTM D5456-10a. The design value for longitudinal shear was selected based on the most conservative value provided by European CLT manufacturers, whose products are tested and approved under the Eurocode certification system (Finnforest Merk, 2008).

The material performance values that were used in the CLT structural design calculations were considered conservative estimates when compared to the accepted structural design values for glued-laminated timber in Canada. Refer to Table 1 for a

comparison of the MPB-killed lodgepole pine CLT design values to the Spruce-Lodgepole Pine-Jack Pine (S-P) values, as listed in Table 6.3 of CAN/CSA-O86-01 (2005). See APPENDIX A – Structural Design Calculations for a computational derivation of the CLT design values, as based on the testing done by Lam & Chen (2008) and Chen (2009; 2011), as well as structural design examples for typical CLT floor and roof plates.

Structural Design Criteria	<b>Cross-Laminated Timber</b> (MPB Lodgepole Pine)	Spruce-Pine Glulam (CAN/CSA-086-01)
Bending moment $-f_b$ (MPa)	23.1	25.6
Compression parallel $-f_c$ (MPa)	20.6	25.2
Longitudinal shear $-f_v$ (MPa)	1.4	1.75
Modulus of elasticity – $E_s$ (MPa)	10,050	10,300

Table 1 – Specified Design Values: CLT vs. CAN/CSA-O86-01

#### 2.2.3 – Glued-Laminated Timber

Glued-laminated timber (glulam) was employed as a substitute for the above grade reinforced concrete columns and beams in the redesign of Discover Place – Building 12. Glulam has been tested and used extensively in the EU and North America for over 20 years. It consists of sawn lumber lamellas that are face glued to one another and finger jointed when required for large span applications. Glulam has the ability to be used as both a horizontal and/or vertical force carrying member. The redesign of Discovery Place used glulam beams to support the above grade CLT floor and roof slabs (see Figure 3), as well as employing glulam to act as exterior spandrel beams that bear the vertical load of the curtain wall assembly and act as a horizontal force transmission system for wind loading. Glulam columns were also designed from the ground floor to the underside of the roof level, maintaining the same column layout that existed in the reinforced concrete building design.

The glulam beams and columns were designed based on the Canadian standards set out in CAN/CSA-O86-01, see APPENDIX A – Structural Design Calculations for example design calculations. The material properties that were used for the glulam beam and column designs were also obtained from the Engineering design in wood standard, under the wood species group Spruce-Pine. All the interior and spandrel beams and the majority of the columns were designed using the 20f-E and 12c-E glued-laminated timber stress grades, respectively (as per Table 6.3 of CAN/CSA-O86-01). The design of the vertical columns used a combination of both S-P 12c-E stress grade and Douglas Fir-Larch (D.Fir-L) 16c-E stress grade glulam. From floors two through five, 12c-E stress grade glulam was adequate to meet the specified structural loading, whereas from the ground floor to the second, D.Fir-L 16c-E, a structurally stronger stress grade, was required to meet the loading scenario. A graphical depiction of glulam columns and beams supporting a CLT floor plate is shown as Figure 3.



Figure 3 – Glulam beam and column frame with CLT floor (Martinsons, 2006, p. 36)

#### 2.2.4 – Gravity Loading

The gravity loading redesign of Discovery Place – Building 12 was based on standards and criteria outlined in the British Columbia Building Code (Government of British Columbia, 1998) and the National Building Code of Canada (NRCC, 1995). The specified live and superimposed dead loads (SDL) that were used in the redesign were taken from the structural engineering drawings, produced by RJC Consulting Engineers (2007) and are shown in Table 2. The self-weight of the concrete and timber systems are
not included in the SDL, as listed in Table 2, but are considered separately in each design case as dead loads (DL). The live load (accounting for occupancy loading), as well as the SDL (accounting for floor toppings, finishes, and mechanical ductwork), were held constant in both the concrete and timber-framed design cases. The self-weight of the concrete and timber structures were reasonably dissimilar, as the density of CLT and glulam is approximately five times less than that of cast-in-place reinforced concrete.

Load Location	Live Load (kPa)	SDL (kPa)
Roof	Snow + Rain = 2.6 + 0.6	1.2
Office Floors	3.1	1.2
Roof Terraces	4.8	3.6
Stairs & Corridors	4.8	_

Table 2 – Specified Live Loads and Superimposed Dead Loads (RJC, 2007)

All beams and columns were designed for both strength and serviceability considerations (see APPENDIX A – Structural Design Calculations for sample calculations). Strength criteria were based on ultimate limit states design principles and maximum deflection limits were imposed to ensure adequate serviceability conditions were obtained. The deflection limits that were used in the design were taken from the Wood Design Manual (CWC, 2005, p. 15) and are as follows:

Location	Total Load Deflection Limit	Live Load Deflection Limit
Roof	L/180	L/240
Typical Floors $(2^{nd} - 5^{th})$	L/180	L/360

Table 3 – CLT and Glulam Deflection Limits (CWC, 2005, p. 15)

The timber redesign of Discovery Place was undertaken from only the grade level to the roof. There has been no alteration to any below-grade portion of the building, despite the fact that it would be possible to reduce the volume of concrete used in the foundations supporting the above-grade timber structure; as the weight of the superstructure was reduced two fold by the substitution of laminated timber for reinforced concrete. The ground floor slab, the three underground parking levels, and the spread footing foundations all remained the same dimensions and were constructed out of reinforced concrete as per the original structural drawings (RJC, 2007). Durability concerns and lack of any present-day case study examples for a building of this size and use, made it unfeasible to design the underground parking levels and foundation structure with wood. Discovery Place – Building 12 was redesigned with EWPs from the top of the ground floor concrete slab upwards; utilizing CLT floor plates, along with glulam beams and columns, as well as concrete elevator and stair cores as the primary structural support system.

#### 2.2.5 – Lateral Loading

The lateral force resisting system of Discovery Place – Building 12 was designed to resist both horizontal wind and earthquake loads. The load path took place through the building by the wind force initially coming into contact with the structural curtain wall system, was then transferred through the floor diaphragm which consisted of glulam beams and CLT floor elements, and finally into the concrete elevator cores and shear walls, which dissipated the load to the below-grade foundation. See Figure 4 for a generalized schematic of a glulam frame and concrete core, recalling that CLT floor plates will be spanned between the glulam floor beams and roof beams.



Figure 4 – Example of a Glulam Frame with Concrete Shear Core (Karacabeyli, 2009)

The wind forces were calculated based on the NBCC (2005) methodology and a summary of the loading computation can be found in APPENDIX A – Structural Design Calculations. The design wind loadings that were used are identical to the wind loads shown in the issued-for-construction structural engineering drawings (RJC, 2007) and are listed as follows:

 $q_{30} = 0.44 \text{ kPa}$   $q_{10} = 0.36 \text{ kPa}$  Net factored roof uplift = 0.96 kPa

In order to ensure a suitable margin of safety and reliability against earthquake resistance, it was decided that the redesigned timber building would maintain the primary racking force transmission system, as they were designed in the original structural engineering drawings (RJC, 2007). The original lateral force transmission system consisted of reinforced concrete elevator and stair cores, along with a principal interior shear wall. This was considered a conservative design scenario based on the preliminary assumption that the calculated base shear of the timber building would be less than that of the concrete building, due to a reduction in self-weight when moving from a reinforced concrete to a laminated timber structural system. The validity of this assumption was confirmed after the seismic loading scenarios were calculated (see APPENDIX A – Structural Design Calculations for seismic loading comparisons of the reinforced concrete- and heavy timber-framed design alternatives).

The seismic force derivation and distribution was based on the principles outlined in the BCBC (1998). The seismic design coefficients were obtained from the structural engineering drawings (RJC, 2007) and were as follows:

$$Za = 4, Zv = 4$$
  
 $v = 0.2$   
 $I = 1.0$   
 $F = 1.0$ 

Currently, there are no Canadian structural design values for the in-plane shear resistance of CLT. The shear capacity of CLT has shown good results for high horizontal cyclic loading, making it a suitable candidate as a seismic force resisting system. An Italian research team noted that the CLT panels behaved almost completely rigid, with localized failures occurring predominantly in the steel connections (Ceccotti et al., 2006). There has also been two full scale shake table tests performed under the SOFIE project, which investigated both three and seven storey CLT buildings under the 1995 Kobe earthquake record. The lead researcher of the SOFIE project remarked that

"the test building has been shaken at least with 15 "destructive" quakes in a row without any significant repairs. In addition, even the quake producing the nearcollapse state was not able to permanently deform the building as it was still standing straight and vertical at the end of the entire set of shakes" (Ceccotti, 2008, p. 164).

Based on the in-plane strength, stiffness, and seismic response research performed in the EU (Ceccotti et al., 2006; Dujic et al., 2008; Bogensperger et al., 2010; Dujic et al., 2010) the CLT plates were considered to be an adequate lateral force transmission system that was capable of acting as a horizontal shear diaphragm, transferring both wind and earthquake loads to the interior shear walls and cores of Discovery Place – Building 12. Popovski et al. (2010) tested the lateral load resistance of several CLT wall configurations and connection details; concluding that "CLT walls can have adequate seismic performance when nails or screws are used with steel brackets".

The lateral loading scenario of the timber-framed building could only be carried out when an appropriate ductility-related force modification factor (R) was determined. The horizontal CLT diaphragm was considered flexible when compared to the stiff concrete cores and shear walls. Despite the BCBC (1998) not containing any R values for a flexible CLT seismic force resisting system, it was considered reasonable and conservative to assume the ductility modification factor would be similar to nailed shear wall panel with plywood, waferboard or OSB, as per Table 4.1.9.1.B., BCBC (1998) and equal to 3.0. As is shown in APPENDIX A – Structural Design Calculations, the static

loading of the timber building due to seismic effects was based on R equal to 3.0. By comparison, the seismic loading of the concrete-framed building was based on R equal to 3.5, as per the issued-for-construction design drawings (RJC, 2007).

#### 2.2.6 – Exterior Envelope

The building enclosure was redesigned by substituting wood products where concrete or steel existed in the original design. This included the substitution of CLT panels for the 229 mm (9 in) deep reinforced concrete roof slab and the 152 to 254 mm (6 to 10 in) thick concrete exterior walls. The steel studs specified in the exterior wall assembly of the original architectural drawings (Bunting Coady Architects, 2007) were removed and the gypsum finish was fastened directly to the load-bearing CLT wall elements. The visible glazing in the curtain wall assembly was left unchanged in the timber building redesign and there were small modifications to the spandrel section of the curtain wall; that is, the steel studs originally specified, were replaced with wood studs in the spandrel back panels of the curtain wall makeup, the rigid insulation thickness was decreased 6 mm and a 25 mm air gap was inserted.

In order to maintain functionally equivalency of both the concrete and timber building designs, it was necessary to ensure the timber building enclosure (roof, exterior and curtain walls) had the same heat resistance (RSI) values as the concrete building. Having consistent RSI values in both the concrete- and timber-framed building designs, ensured that over each building's life cycle, the operational energy use would be equivalent in either design case. It was necessary to reduce the cross-sectional depths and in some cases remove insulation material entirely, in order to obtain an RSI value in the timber building design. A more detailed comparison of the building envelopes of both design scenarios is given in Section 4.1.2 – Building Design and APPENDIX B – Building Envelope Design.

### 2.3 – Life Cycle Assessment

In North America, over the last two decades, there has been a widespread interest and effort by the design and construction communities to reduce the impact of built infrastructure on the natural environment. Designer's and product manufacturer's newfound concern for sustainability, along with a more widespread public interest in the interaction between the built environment and the natural world, has led to the formation of metrics and measurement tools by which to compare product and process design alternatives on the basis of environmental merit.

A direct result of the oil crisis and energy shortages of the 1970s was the need to improve industrial production efficiency with respect to energy and resource consumption, in order to maintain economic competitiveness. This led to the emergence of a throughput analysis technique, life cycle assessment (LCA); originally developed to track material and energy flows in industrial processes and systems. The underlying ideology of LCA has not changed since its conception; "input and output data were collected for each unit process identified within the system, using standard mass and energy balance partitioning and calculation techniques, then aggregated together to generate a sum total of resources used, energy consumed, and environmental emissions released..." (Cascio, 1996, p. 281). In the contemporary context, "life cycle assessment has been generally accepted within the environmental research community as the only legitimate basis on which to compare alternative materials, components and services" (Cole, 1999, p. 335); it "is the recognized international approach to assess the environmental merits of products or processes" (CWC, 2004, p. 4). The International Standards Organization (ISO) describes LCA as a methodology that "assesses, in a systematic way, the environmental aspects and impacts of product systems, from raw material acquisition to final disposal..." (CAN/CSA-ISO 14040, 2006). It is important to note that LCA, in this study, was used as a building design and product comparison tool focusing solely on environmental consequentiality, directly resulting from a product's life cycle stages (raw materials acquisition, manufacture, use, and disposal). LCA aids in determining what design alternative will produce higher or lower environmental consequences throughout its respective life cycle. See Figure 5 for a schematic representation of the stages of a product's life cycle. LCA, in this study and in its current

scientific format, does not yet take into consideration any indicators from the economic or social sciences. In the context of building design and construction, LCA provides a systematic framework that can be used to measure the environmental advantages and disadvantages of competing building product and construction system choices. The positive attributes of LCA are eloquently described by Lippiatt (2007, p. 4):

"The strength of environmental life-cycle assessment is its comprehensive, multidimensional scope. Many green building claims and strategies are now based on a single life-cycle stage or a single environmental impact. A product is claimed to be green simply because it has recycled content, or accused of not being green because it emits volatile organic compounds (VOCs) during its installation and use. These single-attribute claims may be misleading because they ignore the possibility that other life-cycle stages, or other environmental impacts, may yield offsetting impacts...LCA thus broadens the environmental discussion by accounting for shifts of environmental problems from one life-cycle stage to another, or one environmental medium (land, air, water) to another. The benefit of the LCA approach is in implementing a trade-off analysis to achieve a genuine reduction in overall environmental impact, rather than a simple shift of impact."



Figure 5 – Stages of a Product's Life Cycle (UNEP, 2005, p. 14)

A broad framework for a LCA study is defined by the Canadian Standards Association (CSA), the ISO and the United States Environmental Protection Agency (USEPA) through CAN/CSA-ISO 14040:06, CAN/CSA-ISO 14044:06 and LCA: Principles and Practice (USEPA, 2006). These documents outline the basic principles, requirements and guidelines that must be adhered to when conducting a LCA on any type of product, process, service or system. The CAN/CSA-ISO standards mandate that four main stages of an LCA (goal and scope definition, inventory analysis, impact assessment and interpretation) that interact and affect one another during the course of the study. These individual stages are required be documented, discussed and quantified where possible. Figure 6 shows a flow diagram of the LCA stages and framework. More specifically, ASTM International has produced a guide that is tailored to the LCA of building materials and products; ASTM E 1991 (2005). This LCA research study conducted on the comparison of alternative concrete- and timber-framed building design scenarios of Discovery Place – Building 12, has adhered to the framework, guidelines and principles set forth in the above mentioned CAN/CSA-ISO, USEPA and ASTM International standards.



Figure 6 – Life Cycle Assessment Framework (CAN/CSA-ISO 14040, 2006)

#### 2.3.1 – Goal and Scope Definition

The goal of the LCA was to compare, with respect to environmental impacts, the advantages and disadvantages of constructing Discovery Place – Building 12, a typical mid-rise, five-storey office building from either cast-in-place reinforced concrete or heavy timber (glulam and CLT). The reason for carrying out the LCA study was to determine what building system provided a more environmentally preferable design option, when considering different design scenarios of the building structure and envelope. The results of the study are intended to be used by designers, developers, investors, government decision makers and any other stakeholders (product manufacturers, community groups, etc.) to better inform them of the environmental impacts of different material choices and design options, when considering mid-rise office building construction in the Pacific Northwest of Canada and the United States.

This LCA study will focus only on the direct and indirect environmental impacts of the structural and building enclosure (envelope) systems. The building materials and their corresponding functional units that were considered in the comparison of the concrete- and heavy timber-framed designs are presented in Table 4, as follows:

Table 4 – Building Materials and their	• Corresponding Functional Units
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Concrete Design	Timber Design	Functional Unit	Notes & Assumptions
Gypsum Wall Board	Gypsum Wall Board	$0.09 \text{ m}^2 (1 \text{ ft}^2)$	13 mm ( <sup>1</sup> / <sub>2</sub> ") thick, includes tape, mud, screws @ 406 mm (16") O/C studs, corner bead is not included
Steel Stud Framing		$0.09 \text{ m}^2 (1 \text{ ft}^2)$	33 mm galvanized studs @ 610 mm (24") O/C, screws included
	Wood Stud Framing	$0.09 \text{ m}^2 (1 \text{ ft}^2)$	38 x 89 mm (2"x4" nominal), untreated, kiln-dried @ 406 mm (16") O/C, galvanized steel nails included
	BioPreserve Soyguard Wood Sealer	$9.29 \text{ m}^2 (100 \text{ ft}^2)$	Applied to exterior exposed wood only, repeated every 2 years
Anonymous R-13 Insulation	Anonymous R-13 Insulation	$0.09 \text{ m}^2 (1 \text{ ft}^2)$	89 mm (3-1/2") thick
Spray Foam Insulation		1 m <sup>2</sup>	3 cm thick, closed cell polyurethane with H <sub>2</sub> O/CO <sub>2</sub> blowing agent
Slab-on-Grade	Slab-on-Grade	0.09 m <sup>2</sup> (1 ft <sup>2</sup> )	102 mm (4") thick, f°c = 21 MPa, 15% & 20% fly ash cement mixes considered, assumed 0.908 kg/m <sup>2</sup> (1.67 lbs/yd <sup>2</sup> ) of reinforcing steel
Below-Grade Foundation Walls & Spread Footings	Below-Grade Foundation Walls & Spread Footings	$0.09 \text{ m}^2 (1 \text{ ft}^2)$	203 mm (8") thick, f <sup>°</sup> c = 21 MPa, 15% & 20% fly ash cement mixes considered, assumed 23.9 kg/m <sup>2</sup> (44 lbs/yd <sup>2</sup> ) of reinforcing steel
Above-Grade Walls, Beams, Slabs, Drop Panels & Slab Bands		0.0283 m <sup>3</sup> (1 ft <sup>3</sup> )	f <sup>°</sup> c = 28 MPa, 15% & 20% fly ash cement mixes considered, average of 86.2 kg/m <sup>3</sup> (145 lbs/yd <sup>3</sup> ) of reinforcing steel assumed
Columns & Shear Cores/Walls	Elevator & Stair Concrete Shear Cores/Walls	0.0283 m <sup>3</sup> (1 ft <sup>3</sup> )	f <sup>°</sup> c = 34 MPa, 15% & 20% fly ash cement mixes considered, average of 172.4 kg/m <sup>3</sup> (290 lbs/yd <sup>3</sup> ) of reinforcing steel assumed
	Cross-Laminated Timber Walls & Floors	1 m <sup>3</sup>	38 x 140 mm (2"x6" nominal) untreated, kiln-dried, MPB-killed lodgepole pine lumber, bonding adhesives are included
	Glulam Beams & Columns	1 m <sup>3</sup>	Standard grades and dimensions, untreated, kiln-dried, MPB-killed lodgepole pine lumber, bonding adhesives are included
Curtain Wall	Curtain Wall	1 m <sup>2</sup>	Viewable & spandrel glazing considered, viewable units assumed double-glazed, low-e, argon gas filled
	Generic Cedar Siding	$0.09 \text{ m}^2 (1 \text{ ft}^2)$	Bevelled, 13 mm ( <sup>1</sup> / <sub>2</sub> ") thick, 150 mm (6") wide, galvanized nails @ 41 cm (16") O/C, 1 coat primer & 2 coats stain (stain reapplied every 10 years)

The system boundary of the LCA study was cradle-to-gate, considering a 50-year building lifetime horizon. The environmental burdens associated with each product were considered from raw materials acquisition, through the manufacture/processing stages, accounting for the production and use of fuels, electricity and heat, as well as taking into account transportation/distribution impacts at all points along the product supply chain. The boundaries of the study began at the raw materials extraction and finished at the entrance to the construction site gate, with the inclusion of building material and component replacement over the course of the 50-year life cycle. See Figure 7 for a visual depiction of the study boundary conditions.

Capital manufacturing equipment and human activity were both excluded from the study system. This is relatively common practice in the LCA community, as it is generally accepted that the environmental effects of manufacturing and installing capital equipment are minor when compared to the throughput of materials over the equipment's useful lifetime (Lippke & Bowyer, 2007). For example, the manufacture and installation of a wood planer would not be included in the LCA of glued-laminated timber. Human activity will also have an influence on the environmental impact of building material production but the quantification methods are complicated and data availability is low. Therefore, the environmental impact of human activity was ignored from the quantitative LCA results.

The operational life cycle phase of the building and the associated resource consumption, energy use and emissions generation are not considered in this study. The operational phase of the building's life cycle was omitted in order to focus the LCA study on the comparison of the construction materials. The building envelope in both the concrete and timber design scenarios have the same RSI values and are therefore functionally equivalent, with respect to the heat resistance. Assuming occupant behaviour is unchanged in the alternative design scenarios; both the concrete- and heavy timber-framed buildings will use the same amount of operational energy over their respective 50-year lifetimes.



Figure 7 – Cradle-to-Gate LCA System Boundary (Krogmann et al., 2008, p. 12)

The life cycle inventory (LCI) data for the building products includes recycling and reuse when appropriate pre- or post-consumer inputs exist but does not quantify the end-of-life environmental impacts that result at the conclusion of the building's assumed lifetime of 50 years. The reason that this cradle-to-gate approach was pursued is based solely on data availability restrictions. All relevant and Canadian specific building material LCI data sets consisted only of cradle-to-gate boundary conditions, with little or no quantitative environmental flow information for end-of-life scenarios. Figure 7 gives a diagrammatic representation of the difference between cradle-to-gate (dashed blue line) and cradle-to-grave LCA of a building system (solid black line).

It is important to note that this LCA study uses energy mixes, manufacturing data and typical construction practices that are, at this present point in time, relevant to the Pacific Northwest region of North America. The numerical results of this study cannot be assumed to hold in other geographic locations or elsewhere in the world, where manufacturing and construction techniques may differ significantly. The LCA results are also temporally significant, in reference to energy generation, manufacturing technology, building design and construction techniques. The analysis represents current North American design and construction practice over the last 10–15 years. Changes in manufacturing technology, energy generation practices, building design and construction requirements have the ability to influence the results of this study, if it is repeated at a later date.

### 2.3.2 – Life Cycle Inventory Analysis

The life cycle inventory (LCI) of a product is a tabulated "compilation and quantification of inputs and outputs for a product throughout its life cycle" (CAN/CSA-ISO 14040, 2006). For this study, manufacturing and product LCI data was collected for all the material inputs listed in Table 4. A combination of publicly available North American databases (BEES<sup>®</sup> 4.0, ATHENA<sup>®</sup> and the US LCI Database) and on-site factory measurements (CST Innovations, 2009) were used to account for the material, energy and emissions flows that occurred throughout the raw material acquisition, manufacturing and transportation phases of each building product's life cycle. Table 5 illustrates all the building materials that were included in the study and specifies the LCI data was gathered according to the ISO 14040 defined categories, which include but are not limited to: energy (both non-renewable and renewable) inputs, raw material inputs, products, co-products, waste and emissions to air, water and soil.

The vast majority of the LCI data for this study was collected through the analysis of product supply chains and on-site measurements of raw materials acquisition operations and manufacturing facilities within North America. The only exception to this was the LCI data used for closed cell spray polyurethane foam (ccSPF) insulation. Very little relevant and reputable North American LCI data could be found for ccSPF insulation. This is most likely because it is a relatively new product to the ICI building market; introduced to North America only in the last decade. LCI data for ccSPF was

based on studies conducted in both Spain and Canada, with European data being obtained from Slovay Fluor GmbH, a producer based in Hannover, Germany and Canadian data published by Harvey (2007).

Building Material	LCI Data Source
Gypsum wall board	(1)
Steel stud framing	(1)
Wood stud framing	(1)
BioPreserve soyguard wood sealer	(1)
Anonymous R-13 insulation	(1)
Closed cell spray polyurethane foam insulation (ccSPF)	(3) & (4)
Slab-on-grade	(1)
Below-grade foundation walls & spread footings	(1)
Above-grade concrete walls, beams, slabs, drop panels & slab bands	(1)
Concrete columns	(1)
Cross-laminated timber walls & floors	(5), (6), (7) & (8)
Glulam beams & columns	(5), (7) & (9)
Generic cedar siding	(1)
Curtain wall – vision glass & spandrel	(2)

Table 5 – LCI Data Sources for Building Materials

- (1) Building for Environmental and Economic Sustainability (BEES® 4.0)
- (2) ATHENA® EcoCalculator for Assemblies Vancouver High-Rise v2.3
- (3) LCA of Rigid PU Sprays (Krähling et al., 2001)

\*Data unavailable for fossil fuel depletion & water intake categories

- (4) Net Climatic Impact of Solid Foam Insulation Produced with Halocarbon and Non-Halocarbon Blowing Agents – (Harvey, 2007)
- (5) CORRIM: Phase I Final Report, Glulam Beams PNW & SE (Puettmann & Wilson, 2004)
- (6) CST Innovations Ltd. Igor Zaturecky, 2009
- (7) US Life Cycle Inventory Database NREL, U.S. Department of Energy
- (8) A Cradle-to-Gate LCA of Canadian Softwood Lumber (ASMI, 2009)
- (9) Gate-to-Gate LCI of Glued-Laminated Timbers Production (Puettmann & Wilson, 2005)

#### 2.3.3 – Environmental Impact Assessment

The life cycle impact assessment (LCIA) phase of this study was employed to relate the LCI data from each building product to the occurrence of a potential environmental impact in the natural world. There are several different types of LCIA methodologies that aim to characterize the impacts of the material, energy inputs and outputs that were identified in the LCI data sets, although "there are no generally accepted methodologies for consistently and accurately associating inventory data with specific potential environmental impacts" (CAN/CSA-ISO 14040, 2006). The LCA comparison study of Discovery Place – Building 12 used the environmental impact assessment method developed by the USEPA in the late 1990s. The Tool for the Reduction and Assessment of Chemical and other environmental Impacts (TRACI) was conceived by its inventors to be used within the framework of LCA and was specifically built to reflect potential environmental effects that occur regionally within North America, along with taking into account global environmental phenomena and causalities (Bare et al., 2003).

The life cycle comparison of alternative design scenarios for Discovery Place – Building 12 included an array of environmental impact indicator categories. A number of impact category indicators that were derived by the TRACI program, as well as impact categories and the corresponding indicators that were perceived as industry specific metrics to the building and construction sector were utilized in the LCIA approach. The following environmental impact categories and their respective indicator dimensions, shown in Table 6, were used to compare the potential environmental effects of the concrete and heavy timber design cases of Discovery Place – Building 12.

Environmental Impact Category	Impact Indicator
	<u>^</u>
Global warming potential (GWP)	Carbon dioxide $(CO_2)$ eq.
Acidification potential	Hydrogen ion [H <sup>+</sup> ] eq.
Eutrophication potential	Nitrogen (N) eq.
Fossil fuel depletion	Surplus gigajoules (GJ)
Water intake	Litres (L)
Criteria air pollutants	Disability-adjusted-life-years (DALYs)
Ecological toxicity	2,4-dichlorophenoxy-acetic acid (2,4-D) eq.
Human health; non-carcinogenic	Toluene $(C_7H_8)$ eq.
Human health; carcinogenic	Benzene $(C_6H_6)$ eq.
Ozone depletion	Chlorofluorocarbon-11 (CFC-11) eq.
Smog formation potential	Nitrogen oxides $(NO_x)$ eq.
Energy Accounting	Indicator
Embodied energy; renewable & non-renewable	Terajoules (TJ)
Embodied energy; feedstock & process	Terajoules (TJ)

\*eq. = equivalents

\*\*Smog a.k.a. Tropospheric/Photochemical ozone

\*\*\*Embodied energy a.k.a. Primary energy

After the LCI data was collected, it was classified into one or more of the above impact categories; according to the TRACI framework, which organizes chemical and other emissions into the relevant impact categories and provides factors in order to facilitate environmental impact equivalency conversion between substances (e.g. due to its molecular properties, 1 kg CH<sub>4</sub> has the same global warming potential as 23 kg of CO<sub>2</sub>). The last step in the LCIA stage was characterization; which included the calculation of category indicator results, based on the distinct environmental impacts of different chemicals and emissions as outlined by the USEPA's TRACI program. A full and thorough description of TRACI's inner workings; including its development history, definitions of the above mentioned environmental impact categories, including the sophistication level behind the spatial, geographical and temporal resolution of each impact category, the decision-making framework behind the indicator metrics and the derivation of environmental impact conversion values was published by Bare (2002) and Bare et al. (2003).

The LCIA process would not have been possible without first performing a material take-off of each building product on both the concrete and timber building design cases. The material take-offs were quantified with reference to the defined functional units, as shown in Table 4. The environmental impact indicator quantities (tonnes  $CO_2$  eq., tonnes N eq., TJ of embodied energy, etc.) were calculated separately for each building product in the concrete-framed design scenario. This process was repeated for the calculated material quantities required in order to produce a functionally equivalent building with laminated EWPs and sawn lumber. It was then possible, by considering each design scenario separately, to sum the cumulative effects of the different building products that occurred under each impact category; thereby generating two whole building cradle-to-gate LCIA profiles that included 14 different building elements (Table 4), evaluated using 11 environmental impact categories (Table 6).

The LCIA stage of this project did not use any grouping, weighting or normalization techniques in an attempt to create and compare the concrete and timber building alternatives using a single quantitative environmental impact measurement. Instead, the LCIA environmental comparison was made by contrasting both building design scenarios under each of the 11 impact categories, as shown in Table 6.

#### 2.3.4 – Cross-Laminated Timber

Less than two decades ago, cross-laminated timber (CLT) was introduced as a viable structural system for mid-rise building construction in the EU. At the present time, there are between five and ten major CLT manufacturing facilities currently supplying large volumes of customized CLT panels to the European building development market. The supply situation is much different in North America; neither Canada nor the United States operates a large-scale CLT manufacturing factory. In order to develop the LCI data set for CLT produced with Canadian lumber and manufactured at a North America facility, it was first necessary to understand the production process of CLT and then obtain North American specific LCI data for the raw materials acquisition, transportation and manufacturing phases of the product's life cycle. The first step in developing the LCI and LCA profiles of CLT was to perform a mapping outline of the life cycle phases of the product. Figure 8 shows a flow chart depiction these life cycle phases of CLT.



Figure 8 - Life Cycle Phases of Cross-Laminated Timber

The LCI data collection of North American made CLT was consistent with the cradle-to-gate study boundary conditions that were set out in Section 2.3.1 – Goal and Scope Definition. Inputs, outputs, wastes and emissions data were collected for only the raw materials acquisition (timber harvest) and production (sawmill and CLT manufacturing) phases of the product's life cycle. The environmental burdens associated with transportation during the raw materials acquisition and production/manufacturing was included, as per the US LCI database. The environmental impacts resulting from the on-site panel installation, maintenance and the end-of-life phases were outside the study boundary and were not quantitatively included in the comparative LCA of Discovery Place – Building 12.

Multiple data sources were used to develop the LCA profile of CLT. *A Cradleto-Gate Life Cycle Assessment of Canadian Softwood Lumber*; a study produced by the Athena Sustainable Materials Institute (2009) was used to compile the LCA data for the average environmental impacts of tree harvesting activities, dimensional lumber production and the associated transportation impacts for softwood lumber produced in Canada. The study used on-site data collection from multiple sources across Canada, in conjunction with the USEPA's TRACI environmental impact characterization tool, to develop the average LCA profile for one thousand board feet of softwood lumber in Canada. The ASMI (2009) study covered all 11 environmental impact categories that were listed in Table 6 – Environmental Impact Categories and Indicators.

In order to develop the LCA profile of the manufacturing stage of CLT, it was necessary to understand the production sequence, along with the materials and energy requirements to make CLT panels in Canada. Close collaboration and a knowledge sharing relationship with CST Innovations Ltd., an EWP manufacturing company located in New Westminster, British Columbia, was necessary to understand and document the CLT manufacturing process. CST Innovations Ltd. operated a pilot scale CLT production facility, with an average manufacturing volume of approximately 1.4 m<sup>3</sup> (50 ft<sup>3</sup>) per day. Personal communication with the plant operator, Igor Zaturecky (*September 18, 2009*), led to the formation of the following schematic representation of the generalized manufacturing process for CLT, shown in Figure 9.

**Input:** 2x4/2x6/2x8-dimensionallumber



3, 5, 7 or 9-ply CLT Panel

Figure 9 – Cross-Laminated Timber Manufacturing Process

LCI data was collected at each manufacturing stage, based on information provided about machine and motor sizes, running times and speed of production at each stage. The LCI data was collected on a per panel basis and included measurements regarding material inputs, waste generation outputs, electricity and propane consumption, along with associated transportation burdens. The production data assumed an output of three panels per day, with each panel having dimensions of 1.22 m (4 ft) wide by 3.66 m (12 ft) long by 99 mm (4 in) deep. All panels were assumed to be a 3-ply system, constructed from 38 x 140 mm (2"x 6" nominal) MPB-killed dimensional lumber, No. 2 grade or better. The LCI data is based on the use of a cold curing method, which uses ambient temperature and a pressure-setting adhesive to bond the lamination layers. The LCI data includes impacts derived from the most commonly used North American finger jointing adhesive, although the burdens associated with cutting and glue application of finger joints is not included. All LCI information considers face bonding of the lamellas, whereas edge bonding and CNC machining processes are not included in the dataset. In order to ensure an equivalent comparison to the reinforced concrete LCI data set, the emissions associated with the electricity usage during the manufacturing stage of CLT were quantified using the average United States electricity mix (Deru & Torcellini, 2007,

p. 8). A tabulated summary of the LCI data obtained from the CST Innovations manufacturing facility can be found in APPENDIX C – LCI/LCIA Data Sets and Summaries. The LCI data obtained from the CST Innovations Ltd. pilot plant manufacturing facility, along with the accompanying transportation burdens during all life cycle stages were then quantified under each environmental impact category using the USEPA's TRACI environmental impact characterization program.

The environmental impacts associated with the use of wood adhesives; in particular phenol resorcinol formaldehyde (PRF) and melamine urea formaldehyde (MUF), the most common adhesives used for structural face bonding and finger jointing of EWPs in North America, was also quantified. LCI data for the production of MUF and PRF adhesives and hardeners was obtained from a study published by Puettmann and Wilson (2004, pp. 16-17) under the CORRIM Phase I project. The appropriate mass and application quantities of PRF and MUF adhesives and hardeners related to CLT production were based on typical glued-laminated timber production (as listed in APPENDIX C – LCI/LCIA Data Sets), as per Puettmann and Wilson (2004). The environmental emissions to air, water and soil that were associated with the production of PRF and MUF adhesives and hardeners was combined with the other manufacturing-related emissions and similarly grouped and quantified using the USEPA's TRACI methodology.

#### 2.3.5 – Glued-Laminated Timber

The LCI data set and the subsequent LCA profile of glued-laminated timbers produced in North America was developed from multiple government and industry data sources. Similar to the study boundary conditions of CLT, only the raw materials acquisition (timber harvest) and production (glulam manufacturing) phases of the product's life cycle were considered in the quantitative environmental analysis. The environmental emissions data associated with the timber harvesting and drying activities was compiled from the Consortium for Research on Renewable Industrial Materials (CORRIM) Phase I Report; *Softwood Lumber – Pacific Northwest Region* (Milota, 2004). The environmental impacts associated with the manufacturing of glulam were also

obtained from the CORRIM Phase I report by Puettmann and Wilson (2004), entitled *Gate-to-Gate Life-Cycle Inventory of Glued-Laminated Timbers Production*. The Puettmann and Wilson (2004) report included the LCI data of the PRF and MUF wood bonding resins, used for face gluing and finger jointing respectively (refer to APPENDIX C - LCI/LCIA Data Sets). The emissions associated with transportation during the raw materials acquisition, manufacturing and from the mill gate to the construction site are all accounted for and estimated using the US LCI database. The TRACI characterization tool was used to group and quantify the environmental impacts of all emissions to air, soil and water that were associated with cradle-to-gate glulam production.

### 2.4 – Summary of Methodology

Discovery Place – Building 12, a 14,000 m<sup>2</sup> (153,207 ft<sup>2</sup>), five-storey, concreteframed structure, located in the Pacific Northwest, was chosen as a case study example of typical North American office building design and construction. The concrete-framed building was structurally redesigned using heavy laminated timber EWPs (glulam and CLT) from the ground floor to the roof. The building envelope was also redesigned using wood products, with careful consideration to maintain equivalent heat resistance values in both the concrete and timber design scenarios. Material take-offs were performed for both the concrete and heavy timber building alternatives. Cradle-to-gate LCA environmental profiles were calculated for all the building products, using relevant North American LCI databases and studies. The North American specific LCA profile of CLT was developed using multiple data sources, including on-site measurements from a pilot manufacturing facility located in British Columbia. The environmental impacts of both the concrete and laminated timber building design alternatives were compared under 11 impact categories and characterized using the USEPA's TRACI program.

## 2.5 – Assumptions and Limitations

There are several underlying assumptions and limitations that, if altered, have the potential to change the outputs of this study. This LCA study is limited by its geographic and temporal scales. The relevancy of the results and conclusions that are drawn from this work cannot be applied unilaterally to other geographic regions, building types or time periods. The findings of this LCA study are based on a steady-state analysis assumption; a finite window of time. Reality, on the other hand, is ever changing; as design considerations, industrial processes and environmental emissions and effects follow dynamic patterns and will continually transform throughout time. The detailed results of this research are directly applicable only to this one case study example; Discovery Place – Building 12 and are valid for design, construction and materials production processes that have taken place in the last 10–15 years. This was a comparative LCA study of only one office building in the Pacific Northwest. It is important to appreciate and understand that buildings are constructed in many different shapes and sizes, with huge degrees of variability throughout the North American marketplace. Due to the large degree of inconsistency in the building sector, the results from this single study cannot be extrapolated to all office buildings or across the ICI building sector in general.

#### 2.5.1 – Building Design Comparison

When considering the functional equivalency of the reinforced concrete- and heavy timber-framed buildings, it is important to note that both these buildings meet minimum acceptable design standards, with respect to structural integrity and building enclosure performance. The redesign of the laminated timber-framed building was not as detailed or iterative as its concrete-framed counterpart. For example, none of the bolted, screwed or angled steel connections were designed or included in the LCA of the heavy timber-framed building. Connection design is a rigorous and detail specific process, and as a result of time and manpower constraints was omitted from the analysis. The structural design process of the timber building consisted of determining worst case loading scenarios for the CLT floor plates and walls, as well as the glulam beams and

columns. These worst case scenarios were then used to design structural members that were subsequently used for all other, less stringent, loading situations. This "brute force" approach to design would be considered "overkill" in the engineering design community and most probably has led to a laminated timber building that has the potential for a significant reduction in material quantities through additional design iterations. The mandate of the timber building redesign was to be sure that it met the minimum structural design guidelines, while minimizing the computational effort. In order to achieve this mandate, the heavy timber-framed building used conservative material property characteristics (refer to Table 1), combined with worst case loading scenarios to produce a building design that was certain to meet and in many instances, exceed the minimum structural performance parameters. Therefore, functional equivalency of the concreteand timber-framed structures does not refer to the direct substitution of one material for another (LCA comparisons cannot simply be concluded on a per weight or volume basis); what functional equivalency refers to is the ability of each building alternative to meet distinct and often material specific minimum acceptable design standards. In the case of this LCA study, functional equivalency does not refer to a design performance- or efficiency-based metric. The notion and measurement of how close each of the building designs came (i.e. efficiency/economy of the design) to a minimum building code regulation or standard was considered outside the scope of this research project.

#### 2.5.2 – Building Material Accounting

During the LCI phase of the study, several building materials and elements were omitted from the analysis. The reason for the omissions, in most cases, was due to lack of LCI data. The building materials that were considered in the LCI analysis are contained in Table 4. All building materials, except the curtain wall system, were considered in each of the 11 environmental impact categories. Due to data unavailability, the curtain wall system was only accounted for the in global warming potential impact category and included in the total embodied energy. The removal of building products and systems such as air intake/exhaust grills, partition walls, interior floor and ceiling finishes, office furniture, lighting, mechanical and electrical systems, etc. from the LCI

analysis was viewed as appropriate. The scope of the study was on alternative construction system selection and most items that were omitted would have needed to be provided, regardless of choosing either concrete or timber as the building support system. With respect to the exclusion of mechanical and electrical systems, their analysis was considered outside the cradle-to-gate boundary of the LCA, as the bulk of their impact occurs during the operational phase of the building's life cycle. The final justification was that the vast majority of the aforementioned building elements were required, in identical quantities, in both the concrete and heavy timber design scenarios; acting to cancel each other out when the design alternatives were compared against one another.

When comparing the building material quantities to the LCI data sources, it was often difficult to represent the exact elements that were depicted in the designs. For instance, this occurred when modelling the exterior wall and roof insulation. The architectural drawings (Bunting Coady Architects, 2007), specified R-12 rigid insulation, but the LCI data set was generated for anonymous R-13 insulation. In both design scenarios, R-12 was replaced with anonymous R-13 insulation. A second case occurred with the concrete strength. The LCI data set (f'c = 28 MPa) for above-grade walls, beams and slabs differed from the specified concrete strength (f'c = 30 MPa) on the structural engineering drawings (RJC, 2007). In this case, the concrete strength was assumed to be 28 MPa to match the LCI data source. With respect to reinforcing steel, it was considered exhaustive to calculate the exact quantities of steel bars contained in the individual footings, walls, slabs, beams and columns; instead, industry average values for reinforcing steel in walls, slabs and columns, contained as part of the reinforced concrete LCI data set, were used (refer to Table 4). All structural steel connections associated with the heavy timber building scenario were not designed and subsequently omitted from the comparative analysis.

The LCI data set that contained information for gypsum wall board, assumed a stud spacing of 406 mm (16 in) on-centre. This was true for the majority of the exterior walls in the concrete and timber building designs, except the curtain wall system's spandrel panels. In this instance, the gypsum board on the back pan of the spandrel panel had a stud spacing of 610 mm (24 in) on-centre. It was not possible to alter the LCI data set to represent the larger 610 mm spacing; therefore, it was assumed that all gypsum had

a stud spacing of 406 mm on-centre. The implications of this assumption have minor relevancy, in that more drywall screws are accounted for in the LCI data set than are actually contained in the building designs.

Finally, the roof and balcony waterproofing membrane (2-ply SBS, modified bitumen) was not included in the LCI analysis. This decision was made for two reasons; (1) there were no relevant North American LCI data sets for the inputs and outputs of 2-ply SBS modified bitumen waterproofing and (2) it was not known if this type of waterproofing was applicable to CLT construction. Due to the lack of local CLT construction examples, the typical North American waterproofing design for a flat roof constructed with CLT structure was not well known. Although an essential component of the building enclosure, the lack of LCI data and limited North American design examples necessitated the omission of the flat roof waterproofing from both the concrete- and heavy timber-framed LCI and LCIA calculations.

### 2.5.3 – Life Cycle Inventory Data Quality

Some of the main types of uncertainty in data quality are due to inaccurate data (poor measurements), data gaps, and unrepresentative (proxy) data (Björklund, 2002). Several different primary and secondary LCI data sources (refer to Table 5) were used in order to generate the environmental impact profiles of the different building materials and the subsequent LCA building comparison of the reinforced concrete and heavy timber-framed design alternatives. The LCI collection procedure ensured that, in all possible cases, the data accurately represented North American production practices, electricity mixes, transportation distances, modes, fuel sources and combustion processes. With respect to transportation distances in the Pacific Northwest, it was assumed that the average round trip distance from the building material manufacturing facility to the construction site gate was 200 kilometres.

The primary LCI data that was collected from CST Innovations Ltd. (2009) was considered to be of high quality. On-site communication with the manufacturer, coupled with documentation of machinery and production times provided quality data that was representative of the CLT production process. It should be noted that LCI data for CLT

production was collected from only one pilot production facility and the LCI input and outputs may change from one producer to another. At the time the study was undertaken, the lack of other North American CLT producers made the collection of additional CLT manufacturing data unfeasible.

All of the secondary LCI data sources that were used in this research project are free and publically available, providing transparency and aiding in reproducibility of the study's results. The secondary LCI data that was utilized in the comparative LCA of Discovery Place – Building 12 was generally considered to be of medium quality (only data for ccSPF was considered low quality) and was collected from multiple, publically available databases and LCA software programs. The majority of the LCI and LCA building material data was gathered from Building for Environmental and Economic Sustainability (BEES<sup>®</sup> 4.0), a freeware program produced by the Building and Fire Research Laboratory, the National Institute of Standards and Technology, with support from the USEPA. The BEES<sup>®</sup> 4.0 LCA results represent the U.S. average industrial production for different building products. The LCI information was collected in several different ways, including, facility-specific measurements, industry experts and manufacturer questionnaires (Lippiatt, 2007). The second LCI data source that was commonly called upon and embedded in many of the BEES<sup>®</sup> 4.0 inventories is the U.S. Life Cycle Inventory (US LCI). The US LCI is also a publically available database that contains LCI data under several different product and process categories, including electricity generation, combustion processes and building products. The Consortium for Research on Renewable Industrial Materials (CORRIM) and the Athena Sustainable Materials Institute (ASMI), both North American based research groups, were also referred to as LCI data sources for the environmental analysis of glulam, Canadian-made softwood lumber and curtain wall systems.

The ccSPF LCI data set was the only source information that was developed outside of North America and contained data gaps in the fossil fuel depletion and water intake categories; for these reasons, the data quality of ccSPF was considered low. The inclusion of fossil fuel depletion in the ccSPF LCI data set could have possibly altered the outcome of this impact category in the concrete-framed design scenario; as "the use of natural gas and oil as a feedstock...for polyisocynate [*a production precursor to* 

*ccSPF*] manufactured in Canada…roughly doubles the computed embodied energy of the insulation" (Harvey, 2007, p. 2863). The timber building design contained no ccSPF insulation in the design, whereas the reinforced concrete design contained over 2,000 m<sup>3</sup>.

#### 2.5.4 – Life Cycle Assessment Framework

LCA, employed as a tool to aid in making product selection decisions or system comparisons, inherently contains fundamental weaknesses and limitations in its analysis framework. The overarching limitation of LCA is the sole focus it takes on the environment. Sustainable building design and product selection requires the inclusion of environmental impacts, in addition to social considerations and economic costing. At the present time, the traditional LCA framework does not include any qualitative or quantitative information on social impacts or economic costs. In order to make a wellrounded, fully informed decision about building system alternatives, stakeholders generally regard social and economic considerations as an integral aspect of the decision making process. Life cycle costing and social life cycle assessment are emergent analysis tools that can be used to aid in quantifying economic costs and social impacts; although the integration and weighting of environmental impacts, social considerations and economic costing still remains difficult and often ambiguous (Reap et al., 2008, Part 1).

The boundary conditions that were assumed for the LCA of Discovery Place – Building 12 consisted of a cradle-to-gate (construction site gate) analysis. This implied that the construction/erection, use and end-of-life phases of the building's life cycle were not numerically quantified in the analysis. In any comparative LCA, the choice of boundary conditions and alternative scenarios will have an impact on the outcome of the study. The reason that this LCA study was chosen as a cradle-to-gate analysis was due to the lack of quantitative LCI data associated with succeeding life cycle stages and the inherent difficulty in attempting to predict future circumstances with confidence.

At present, there is a lack of standardization in the selection process and definition of environmental impact categories (Udo de Haes et al., 2004; Reap et al., 2008). In this comparative LCA study, the selection of the impact categories and the corresponding indicators, which facilitated the comparison of the concrete and heavy timber-framed

structures, was limited to 11 (as per Table 6). The selection of the 11 impact categories that were used in this study were chosen from the USEPA's TRACI impact assessment program. Other impact categories such as soil salinity, erosion, habitat alteration, biodiversity loss, non-toxicological human impacts and land use impacts were omitted due to an inability of effectively representing and quantifying these categories. The addition or removal of impact categories has the ability to influence the overall outcome of this LCA study.

The use of different LCIA characterization frameworks can also yield alternative results. The USEPA's TRACI framework was used in this study, but is only one of several LCIA characterization methodologies that aim to transform LCI data into environmental burdens. The use of alternate LCIA characterization models, such as Eco-indicator 99 or EDIP2003, has the possibility of yielding different study results. This is due to the geographic, spatial and temporal variations, as well as the environmental damage modelling approach (midpoint versus endpoint impact categories) in each characterization methodology. It is important to note that the TRACI characterization model is not foolproof and despite sophisticated environmental modelling techniques, some environmental and toxicological effects are omitted due to lack of current knowledge and adequate quantification measures. At the present time, work is being undertaken to improve environmental characterization techniques, such as TRACI, but uncertainties within LCIA frameworks such as "parameter, model and scenario uncertainties associated with fate, exposure and toxicological characterization are likely to remain high, despite consensus building exercises" (Pennington, 2001, p. 94).

Despite being the most comprehensive, contemporary tool available for making environmental comparisons of building products and systems, LCA is not flawless, as Reap et al. (2008, Part 2, pp. 374-378) showcases, both literally and graphically (Figure 10):

"Life cycle assessment (LCA) stands as the pre-eminent tool for estimating environmental effects caused by products and processes...Despite its popularity and codification..., life cycle assessment is a tool in need of improvement... Lacking dynamic representations or historical data, traditional life cycle

assessment cannot account for environmental and industrial dynamics. Changes in pollution profiles as well as ecosystem responses are averaged, and impacts with sufficiently long delays may even be ignored. Responses to environmental interventions cannot be accurately modeled...Amelioration of these problems will undoubtedly improve LCA's environmental relevance."





(Reap et al., 2008, Part 1, p. 292)

# 3.0 – RESULTS

### 3.1 - Bill of Materials

In order to facilitate the comparison of the reinforced concrete and laminated timber design alternatives of Discovery Place – Building 12, it was necessary to perform a quantities take-off of the building materials that were contained in each design option. Table 7 shows the approximate material quantities that were required to produce functionally equivalent building systems, constructed out of either reinforced concrete or a combination of concrete and timber products. The concrete and timber building designs both meet the requirements set out by the applicable Canadian structural design codes and guidelines. Thermal equivalency was also maintained, as the heat resistance values of the building enclosures in each case are nearly equivalent.

Material Group	Unit of Measurement	Concrete Design	Timber Design
Foundation			
Footings	(m <sup>3</sup> of concrete)	1,408	1,408
Slab-on-grade	(m <sup>3</sup> of concrete)	416	416
Foundation walls	(m <sup>3</sup> of concrete)	834	834
Below-grade columns	(m <sup>3</sup> of concrete)	151	151
P2, P1 & ground floor slabs	(m <sup>3</sup> of concrete)	3,253	3,253
Superstructure			
Primary shear walls & cores	(m <sup>3</sup> of concrete)	1,293	1,293
Vertical load-bearing walls	$(m^3 of concrete or CLT)$	181	128
Above-grade floors & roof	$(m^3 of concrete or CLT)$	3,628	2,950
Above-grade columns	$(m^3 of concrete or glulam)$	268	122
Beams & roof parapet	$(m^3 of concrete or glulam)$	166	947
Wood sealer	(m <sup>2</sup> )	_	1,586
<b>Building Enclosure</b>			
Curtain wall	(m <sup>2</sup> )	2,415	2,415
Cedar siding	$(m^2 of 13 mm thickness)$	_	13,374
ccSPF insulation	(m <sup>3</sup> )	2,134	—
R-13 insulation	(m <sup>3</sup> )	258	115
Steel stud framing	$(m^2 @ 400 mm O/C)$	1,617	—
Wood stud framing	$(m^2 @ 400 mm O/C)$	_	1,617
Gypsum wall board	$(m^2 \text{ of } 13 \text{ mm thickness})$	1,929	1,929

 Table 7 – Material Quantities Comparison (based on 50-year building lifetime)

### 3.2 – CLT: A Geographic Comparison of GHG Emissions

It was deemed important to explicitly examine the global warming potential (GWP) of CLT, as it is a new product in the North American EWP industry and GHG emissions are an impact category that is often highly showcased and frequently perceived by the public as a measurement of a product's environmental merit. Table 8 shows a comparison of the GWP profiles for one cubic metre of CLT, produced in either North America or the central EU. The European data was obtained from Stora Enso, a CLT manufacturer located in Austria. The EU data reflects the 2008 production from the Stora Enso Bad St. Leonhard sawmill. The boundary conditions for both studies is the same; a cradle-to-gate analysis. There are several different assumptions used in each analysis case; these differences are outlined in Table 9.

	North America	Central EU <sup>a</sup>
$(kg \ CO_2 \ equivalent \ per \ m^3 \ CL$		$(lent per m^3 CLT)$
Raw materials acquisition & drying	64.1	10.4
Manufacturing operations & glue production	46.3	28.4
Transportation	14.2	4.1
Carbon storage	-739	-776
Total	-614	-733

(a) – LCA for Cross Laminated Timber (Laihanen, 2009)

	North American CLT	European CLT <sup>a</sup>
Wood species	MPB lodgepole pine	European spruce
Average wood density (kg/m <sup>3</sup> )	409 ( <i>oven dry</i> )	430 (oven dry)
Adhesive type	PRF & MUF	Polyurethane (PU)
Manufacturing facility size	Pilot-plant production	Full-scale production line
CLT panel size (m x m)	1.2 x 3.7	3 x 16
Electricity mix	U.S. average <sup>b</sup>	Austrian average
Transportation distance (km)	200	250
LCI data	Refer to Table 5, above	On-site, KCL Ecodata & Ecoinvent
LCIA model	TRACI	Ecoindicator-99

#### Table 9 – Assumptions in North American and European LCA of CLT Calculations

(a) – LCA for Cross Laminated Timber (Laihanen, 2009)

(b) – Deru & Torcellini (2007, p. 8)

Without taking into account the carbon storage properties of the wood, the comparison of the relative impacts of each life cycle stage are shown as Figures 11 and 12.



\*Carbon storage of wood is not considered





\*Carbon storage of wood is not considered



It should be noted that the comparative results illustrated above were developed using many dissimilar variables and assumptions (as per Table 9) and are offered only as a rough, preliminary estimate of the associated cradle-to-gate GHG emissions. Upon initial examination of Table 8, the numbers seem to indicate that the North American CLT manufacturing process accounts for more GHG emissions than a Europeanproduced product. This difference is justified by the wide range of variability that occurred in the CLT production analyses, including the size of the manufacturing facilities, the type of adhesives used, the electricity mixes and the transportation modes. The difference in size and scale of the European and North American manufacturing facilities, along with the use of different types of bonding adhesives are most likely responsible for the variability in emissions that occurred in the manufacturing operations and glue production phases. The coal-based electricity mix in North America, in conjunction with the predominant use of truck transportation in Canada and the U.S. also contributed to the increased emission levels for North American produced CLT. A more lengthy discussion and explanation concerning the LCA of CLT production in North America is offered in Section 4.1.1.

### 3.3 – Life Cycle Impact Analysis: Building Design Comparison

As shown in Figure 13, the LCIA comparison of Discovery Place – Building 12 illustrated that the laminated timber design scenario had a lower environmental impact than the cast-in-place reinforced concrete building, in 10 of 11 environmental impact categories. In all impact categories except fossil fuel depletion, the laminated timber data was normalized with respect to the concrete data. At a minimum, the heavy timberframed building demonstrated a 14% improvement over its concrete-framed counterpart, while at a maximum; the timber building was estimated to have a contribution to global warming potential that was 71% lower than the concrete design. Fossil fuel depletion was the only impact category where the concrete-framed design was superior, displaying a 6% improvement over the laminated timber scenario. Figure 13 gives an illustrative depiction of the comparative environmental performance of the concrete and timber building design alternatives. In addition, the total embodied energy for each alternative design scenario was calculated and categorized for comparative discussion; with the heavy timber and reinforced concrete building designs having cumulative embodied energy contents of 116 and 66 terajoules, respectively. A summary of cumulative LCIA and EE results, broken down by design scenario and building material can be found in APPENDIX C – LCI/LCIA Data Sets and Summaries.



Figure 13 – Environmental Comparison of the Concrete and Timber Design Alternatives

The following sections contain the LCIA profiles that were calculated for each environmental impact category. Prior to the numerical results in each environmental category, there is a brief explanation of the cause-effect chain of that impact category (mid-point versus end-point effects), including the level of site specificity that was used in the impact assessment methodology and model calculations. The impact category explanations, along with the methodology and model definitions, as defined in the following sections, were developed by the USEPA for the TRACI program (Bare et al., 2003; Lippiatt, 2007). Additionally, within each of the impact categories, a gravity analysis has been performed; whereby quantitatively weighted information is provided, as a percentage, on which building materials were the largest contributors to each particular environmental impact category.

### 3.3.1 – Global Warming Potential

The mid-point indicator that was selected for the GWP impact category was the potential global warming effect of a chemical, based on its radiative forcing over a 100-year time period, expressed as tonnes of carbon dioxide equivalent ( $CO_2$  eq.). The

possible end-point results of global warming include increased instances of disease, coastal area damage, agricultural effects, and forest damage, together with various plant and animal effects. Global warming is a worldwide environmental impact phenomenon.



Figure 14 – GWP of Concrete and Timber Building Design Alternatives



Figure 15 – GWP by Building Material: Concrete Design Case

Figure 15 demonstrates graphically that of the cumulative 5,980 tonnes of CO<sub>2</sub> equivalent GHGs genereated by the raw materials acquisition, manufacturing and transportation of the building materials in the concrete design case, cast-in-place reinforced concrete was responsible for 90% of the total GWP, while the curtain wall system accounted for 8% and all other building materials accounted for the remaining 2% of the total cradle-to-gate GHG emissions.



\*Negative percentage indicates net carbon storage



Figure 16 illustrates the percentage breakdown of the GWP emissions, including both the carbon sinks and sources in the laminated timber building design scenario. The net cradle-to-gate GWP was an output of 1,741 tonnes of  $CO_2$  equivalents, with reinforced concrete and all other building materials being sources of carbon emissions, accounting for 207% and 32%, or 3,604 and 557 tonnes of  $CO_2$  equivalent, respectively. The negative percentages on the bar graph signify that the timber building elements (glulam and CLT) acted as carbon sinks, storing a total of 2,420 tonnes of  $CO_2$  equivalent within the building structure and envelope.

#### 3.3.2 – Acidification Potential

The mid-point indicator that was selected for the acidification impact category was the potential to cause wet or dry acid deposition, expressed as tonnes of hydrogen ion  $[H^+]$  equivalent. The possible end-point results of acidification include plant, animal and ecosystem effects and damage to buildings. Acidification is a regional scale environmental impact phenomenon.


Figure 17 – Acidification Potential of Concrete and Timber Building Design Alternatives



Figure 18 – Acidification Potential by Building Material: Concrete Design Case

Figure 18 demonstrates graphically that of the cumulative 1,557 tonnes of H<sup>+</sup> equivalents genereated by the raw materials acquisition, manufacturing and transportation of the building materials in the concrete design case, cast-in-place reinforced concrete was responsible for 97% of the total acidification potential, while all other building materials accounted for the remaining 3% of the total cradle-to-gate acidification emissions.



Figure 19 – Acidification Potential by Building Material: Timber Design Case

Figure 19 illustrates that of the cumulative 1,346 tonnes of  $H^+$  equivalents genereated by the building materials in the timber design case, cast-in-place reinforced concrete was responsible for 75% of the total acidification potential. CLT and glulam accounted for an additional 16% and 7%, respectively, while all other building materials accounted for the remaining 2% of the total cradle-to-gate acidification emissions in the timber design scenario.

### 3.3.3 – Eutrophication Potential

The mid-point indicator that was selected for the eutrophication impact category was the potential to cause overabundance of nutrient content of water bodies, expressed as kilograms of nitrogen equivalent. The possible end-point results of eutrophication include plant, animal and ecosystem effects, odours and recreational effects and human health impacts. Eutrophication is a regional scale environmental impact phenomenon.



Figure 20 – Eutrophication Potential of Concrete and Timber Building Design Alternatives



Figure 21 – Eutrophication Potential by Building Material: Concrete Design Case

Figure 21 demonstrates graphically that of the cumulative 1,489 kilograms of nitrogen equivalents genereated by the raw materials acquisition, manufacturing and transportation of the building materials in the concrete design case, cast-in-place reinforced concrete was responsible for 95% of the total eutrophication potential, while all other building materials accounted for the remaining 5% of the total cradle-to-gate eutrophication emissions.



Figure 22 – Eutrophication Potential by Building Material: Timber Design Case

Figure 22 illustrates that of the cumulative 1,062 kilograms of nitrogen equivalents genereated by the building materials in the timber design case, cast-in-place reinforced concrete was responsible for 88% of the total eutrophication potential. CLT and glulam accounted for an additional 8%, while all other building materials accounted for the remaining 4% of the total cradle-to-gate eutrophication emissions in the timber design scenario.

### 3.3.4 – Fossil Fuel Depletion

The mid-point indicator that was selected for the fossil fuel depletion impact category was the potential to lead to the reduction of the availability of low cost fossil fuel supplies, expressed as surplus gigajoules (GJ). This impact category addresses only the depletion aspect of fossil fuel resources, while the impacts associated with the extraction and combustion processes were considered in other categories. Fossil fuel depletion considers how the energy intensity (energy input per unit of fuel delivered) required for extraction of coal, oil and natural gas will increase over time, assuming fixed technology and a diminishing resource. The possible end-point results of fossil fuel depletion include shortages leading to the use of other energy sources, which may lead to other environmental and economic effects. Fossil fuel depletion is a global scale environmental impact phenomenon.



Figure 23 – Fossil Fuel Depletion of Concrete and Timber Building Design Alternatives

The fossil fuel depletion impact category analyzes specifically the potential to lead to the reduction of the availability of low cost fossil fuel supplies, while neglecting the environmental impacts associated with extraction (such as methane emissions for coal mining), which are accounted for in other impact categories. The analytical procedure considers and ranks the three most widely used fossil fuels (coal, oil and natural gas) by the energy intensity required for extraction, based on current technology and present global availability. At present, coal is the easiest to extract and the most widely available, giving it the lowest energy intensity (0.25 MJ/kg), followed by oil (6.12 MJ/kg) and then natural gas (7.80 MJ/kg). The reason that the concrete design outperforms the timber alternative in this impact category is due to the fact that the production of cement and steel use large amounts of energy generated predominantly by coal and oil, the two most easily extractable and widely available fossil fuels. Whereas the production of laminated timber largely requires natural gas as the feedstock for the production of adhesives and bonding agents. Natural gas has a fossil fuel depletion characterization factor that is over 30 times higher than coal. The reliance on a natural gas feedstock in the timber design resulted in a larger fossil fuel depletion potential, despite the mass of required fossil fuels in the timber design case being lower than in the concrete design scenario.



Figure 24 – Fossil Fuel Depletion by Building Material: Concrete Design Case

Figure 24 demonstrates graphically that of the cumulative 3,946 GJ of cradle-togate fossil fuel depletion potential, calculated for the building materials in the concrete design case, cast-in-place reinforced concrete was responsible for 97% of the total fossil fuel depletion, while all other building materials accounted for the remaining 3%.



Figure 25 – Fossil Fuel Depletion by Building Material: Timber Design Case

Figure 25 illustrates that of the cumulative 4,208 GJ genereated by the building materials in the timber design case, cast-in-place reinforced concrete was responsible for 61% of the total fossil fuel depletion. CLT and glulam accounted for an additional 23% and 14%, respectively, while all other building materials accounted for the remaining 2% of the total cradle-to-gate fossil fuel depletion potential in the timber design scenario.

## 3.3.5 – Water Intake

The indicator that was selected for the water intake impact category was a value calculated directly from the LCI material data sets; representing the cumulative amount of fresh water used from cradle-to-gate, expressed in thousands of litres. The water intake impact category addresses only the resource depletion and scarcity facets but not the water pollution impacts, which are accounted for in other impact categories. The possible end-point results of water use and depletion include shortages leading to agricultural, human, plant and animal effects. Water intake and depletion is a regional scale environmental impact phenomenon.



Figure 26 – Water Intake of Concrete and Timber Building Design Alternatives



Figure 27 – Water Intake by Building Material: Concrete Design Case

Figure 27 demonstrates graphically that of the cumulative 7,369 kilolitres of water required by the raw materials acquisition, manufacturing and transportation of the building materials in the concrete design case, cast-in-place reinforced concrete was responsible for 98% of the total water intake, while all other building materials accounted for the remaining 2% of the total cradle-to-gate water intake.



Figure 28 – Water Intake by Building Material: Timber Design Case

Figure 28 illustrates that of the cumulative 5,349 kilolitres of water required by the building materials in the timber design case, cast-in-place reinforced concrete was responsible for 90% of the total water intake. CLT and exterior wood sealer accounted for an additional 7%, while all other building materials accounted for the remaining 3% of the total cradle-to-gate water intake in the timber design scenario.

### 3.3.6 – Ecological Toxicity Effects

The mid-point indicator that was selected for the ecological toxicity effects impact category was the potential of a chemical released into an evaluative environment to cause ecological harm, expressed as kilograms of 2,4-dichlorophenoxy-acetic acid (2,4-D) equivalent. The possible end-point results of ecological toxicity include plant, animal and ecosystem effects. Ecological toxicity is a national scale environmental impact phenomenon.



\*2,4-D = 2,4-dichlorophenoxy-acetic acid

Figure 29 – Eco-toxicity Effects of Concrete and Timber Building Design Alternatives



Figure 30 – Eco-toxicity Effects by Building Material: Concrete Design Case

Figure 30 demonstrates graphically that of the cumulative 36,680 kilograms of 2,4-D equivalents genereated by the raw materials acquisition, manufacturing and transportation of the building materials in the concrete design case, cast-in-place reinforced concrete was responsible for 99% of the total ecological toxicity effects, while all other building materials accounted for the remaining 1% of the cradle-to-gate total.



Figure 31 – Eco-toxicity Effects by Building Material: Timber Design Case

Figure 31 illustrates that of the cumulative 30,230 kilograms of 2,4-D equivalents genereated by the building materials in the timber design case, cast-in-place reinforced concrete was responsible for 80% of the total ecological toxicity effects. CLT accounted for an additional 18%, while all other building materials accounted for the remaining 2% of the total cradle-to-gate eco-toxicity effects in the timber design scenario.

## 3.3.7 – Human Health: Criteria Air Pollutants

The mid-point indicator that was selected for the human health – criteria air pollutants impact category was the exposure to elevated particulate matter less than  $2.5\mu$ m, expressed as disability-adjusted life years (DALYs). The DALY metric was developed to measure health losses from outdoor air pollution, accounting for years of life lost and years living with a disability, adjusted for the severity of the associated health conditions. The possible end-point results of criteria air pollutants include toxicological human health effects. Airborne particulate matter and air pollution are a regional scale environmental impact phenomenon.



\*DALYs = Disability-adjusted life-years

Figure 32 – Criteria Air Pollutants of Concrete and Timber Building Design Alternatives



Figure 33 – Criteria Air Pollutants by Building Material: Concrete Design Case

Figure 33 demonstrates graphically that of the cumulative 1.58 DALYs connected to the raw materials acquisition, manufacturing and transportation of the building materials in the concrete design case, cast-in-place reinforced concrete was responsible for 95% of the total criteria air polllutants. ccSPF insulation and all other building materials accounted for the remaining 5% and 1%, respectively, of the total cradle-to-gate criteria air pollutants.



Figure 34 – Criteria Air Pollutants by Building Material: Timber Design Case

Figure 34 illustrates that of the cumulative 1.13 DALYs connected to the building materials in the timber design case, cast-in-place reinforced concrete was responsible for 90% of the total criteria air pollutants. CLT and glulam accounted for an additional 9%, while all other building materials accounted for the remaining 1% of the total cradle-to-gate criteria air pollutants in the timber design scenario.

### 3.3.8 – Human Health: Carcinogenic and Non-Carcinogenic Effects

The mid-point indicator that was selected for the human health – carcinogenic and non-carcinogenic effects impact categories was the potential of a chemical released into an evaluative environment to cause human cancer/non-cancer effects, expressed as tonnes of benzene equivalent and kilotonnes of toluene equivalent, respectively. There are over 200 harmful chemicals that are considered internally within the TRACI characterization analysis, including flows to both air and water. Where LCI data was obtained from sources other than the BEES<sup>®</sup> 4.0 database, only the 25 most important chemical flows were considered (Lippiatt, 2007, p. 21). Although sawdust is now considered a potential carcinogen in some jurisdictions, it was not considered to have any significant human health effect in this analysis. The possible end-point results of carcinogens and non-carcinogens include a variety of specific human cancer and toxicological non-cancer effects, respectively. Human health effects, related to cancer and non-cancer ailments are national scale environmental impact phenomena.



Figure 35 – Carcinogenic Effects of Concrete and Timber Building Design Alternatives



Figure 36 – Non-Carcinogenic Effects of Concrete and Timber Design Alternatives



Figure 37 – Human Health Effects by Building Material: Concrete and Timber Design Cases

Figure 37 demonstrates graphically that of the cumulative carcinogenic (Figure 35) and non-carcinogenic (Figure 36) effects genereated by the raw materials acquisition, manufacturing and transportation of the building materials in both the concrete and timber design cases, cast-in-place reinforced concrete was responsible for over 99% of the total human health effects, while all other building materials accounted for less than 1% of the total cradle-to-gate carcinogenic and non-carcinogenic effects.

## 3.3.9 – Ozone Depletion

The mid-point indicator that was selected for the ozone depletion impact category was the potential to destroy ozone based on a chemical's reactivity and lifetime, expressed as grams of chlorofluorocarbon-11 (CFC-11) equivalent. The possible end-point results of ozone depletion include skin cancer, cataracts, material damage, immune system suppression, crop damage and other plant and animal effects. Ozone depletion is a global scale environmental impact phenomenon.



Figure 38 – Ozone Depletion Effects of Concrete and Timber Building Design Alternatives



Figure 39 - Ozone Depletion by Building Material: Concrete and Timber Design Cases

Figure 39 demonstrates graphically that of the cumulative ozone depletion genereated by the raw materials acquisition, manufacturing and transportation of the building materials in both the concrete and timber design cases, cast-in-place reinforced concrete was responsible for over 99% of the total ozone depletion, while all other building materials accounted for 1% of the total cradle-to-gate ozone depletion effects.

# 3.3.10 – Smog Formation Potential

The mid-point indicator that was selected for the smog formation impact category was the potential to cause photochemical smog, expressed as tonnes of nitrogen oxide  $(NO_x)$  equivalent. The possible end-point results of smog formation include human mortality, asthma effects and plant effects. Smog formation is a regional scale environmental impact phenomenon.



Figure 40 – Smog Formation Potential of Concrete and Timber Design Alternatives



Figure 41 – Smog Formation Potential by Building Material: Concrete Design Case

Figure 41 demonstrates graphically that of the cumulative 29 tonnes of  $NO_x$  equivalents genereated by the raw materials acquisition, manufacturing and transportation of the building materials in the concrete design case, cast-in-place reinforced concrete was responsible for 99% of the total smog formation potential, while all other building materials accounted for the remaining 1% of the cradle-to-gate total.



Figure 42 – Smog Formation Potential by Building Material: Timber Design Case

Figure 42 illustrates that of the cumulative 24 tonnes of  $NO_x$  equivalents genereated by the building materials in the timber design case, cast-in-place reinforced concrete was responsible for 81% of the total smog formation potential. CLT and glulam accounted for an additional 13% and 5%, respectively, while all other building materials accounted for the remaining 1% of the total cradle-to-gate smog formation emissions in the timber design scenario.

## 3.3.11 – Embodied Energy

The indicator selected for the embodied energy category was the cumulative amount of primary energy consumed and stored throughout the raw materials acquisition, product manufacturing and transportation stages (i.e. from cradle-to-gate), measured in terajoules (TJ). Embodied energy was not considered an environmental impact category but was quantified for informative and comparative analysis. The embodied energy was accounted for and classified in two ways; (1) by fuel renewability and (2) by process and feedstock energy. Fuel renewability was separated into energy derived from nonrenewable (petroleum, natural gas, coal and other fossil fuels) and renewable (hydro, wind, biomass, geothermal and nuclear) sources. Process energy accounts for the amount of energy that was released when fuels are utilized or combusted during the production or operation of an industrial process (i.e. burning fossil fuels to operate a factory or a truck). Feedstock energy is the potential energy contained in fuel resources that are extracted from the Earth; such as the potential energy contained in bio-based EWPs or fossil fuel based adhesives and insulation contained within the building's structure and envelope.



\*Nuclear energy is considered to be renewable in this calculation

Figure 43 – Cumulative Embodied Energy of Building Materials by Fuel Renewability



\*Process energy a.k.a. fuel energy

Figure 44 – Primary Energy of Construction Materials (Feedstock vs. Process Energy)

Figures 43 and 44 illustrate that the cumulative embodied energy and the primary energy of the building materials was higher in the laminated timber design than in the reinforced concrete case. The results obtained from the embodied energy comparison of Discovery Place Building 12 are significantly different than other research results, particularily studies that focus on low-rise residential wood-, concrete- and steel-framed structures. A more detailed discussion on embodied energy and a results comparison to other embodied energy research is provided in Section 4.1.3.



Figure 45 – Feedstock Energy Allocated by Building Material: Timber Design Case

Figure 45 illustrates that of the combined 63.1 TJ of feedstock energy associated with the building materials in the timber design case, CLT contained 74% (46.7 TJ) of this energy and glulam accounted for an additional 14% (8.8 TJ), while all other building materials accounted for the remaining 12% of the total feedstock energy in the timber design scenario.



Figure 46 – Process Energy Allocated by Building Material: Timber Design Case

Figure 46 illustrates that of the combined 49.7 TJ of process energy required for the building materials in the timber design case, reinforced concrete required 65% of this energy. CLT and glulam accounted for an additional 19% and 14%, respectively, while all other building materials accounted for the remaining 2% of the total process energy required in the timber design scenario. A cumulative summary of EE results, broken down by design scenario and building material is provided in APPENDIX C – LCI/LCIA Data Sets and Summaries.

## 3.4 – Uncertainty Analysis

Uncertainty is "the discrepancy between a measured or calculated quantity and the true value of that quantity" (Finnveden et al., 2009, p. 14) and appears in almost all stages of an LCA study. The reliability of the LCA results was an important consideration in the comparative LCA of Discovery Place – Building 12. All phases of the study, in particular LCI data collection and LCIA modelling, were undertaken with a high degree of attentiveness and quality control. Despite the level of care taken in conducting the comparative LCA, a degree of uncertainty was, inevitably still present in the results. This uncertainty was derived from several sources including data quality, environmental modeling techniques and system boundary selection to name a few.

In order to accurately quantify uncertainty in numerical terms, it was necessary to be provided with relatively large data sets in which statistical distributions could thereby have been calculated and analyzed. The LCI data sets that were used for building materials did not come with attached statistical distributions and therefore, it was not possible to calculate the uncertainty associated with the LCIA results in numerical terms. All secondary data, primarily from BEES<sup>®</sup> 4.0, ASMI and the US LCI did not contain any information on the associated probabilistic distributions of the data sets. The primary data for the production of CLT was collected from only one pilot plant facility, thereby making it impossible to determine variability across several manufacturing facilities.

This study does not include a numerical uncertainty analysis, as there were no statistical distributions connected with either the primary or secondary LCI data. This made it impossible to calculate distributions associated with LCI data, along with the accompanying confidence intervals and standard deviations in the LCIA results. It is important to keep this in mind when using LCA as a comparative decision making tool. The results generated in this study are based on relevant resource extraction, production and transportation data sources in tandem with scientifically grounded assumptions and estimates. The consequence of the final LCIA results was determined by the quality of the LCI data; input conditions will inevitably be reflected in the output results. LCA results are often viewed through a blurry lens; they are accurate enough to be used for decision making purposes but due to the ever changing nature of technology, manufacturing processes and environmental modelling techniques, LCA results can often have shifting means, medians and absolute values. This is often the case with many past and present LCA studies and must be acknowledged when using LCA as a tool in the decision making process.

It was possible to have assumed and fitted probability distributions to the LCI data and then used these assumptions to calculate the inherent numerical uncertainty of the LCIA results using Monte Carlo methods. This approach was not taken as it was considered to be an exercise that would have clouded and overcomplicated the final results, while providing little additional guidance for decision makers. Instead, the study undertakes several sensitivity analyses, both quantitative and qualitative in nature, that aim to confirm the validity and conservativeness of key assumptions. The subsequent sensitivity analyses also attempted to shed light on the inclusion of alternative life cycle stages and boundary condition scenarios, in an attempt to exhibit the robustness of the study's results.

The LCA study conducted was compiled using a process-based approach. That is, when calculating the environmental effects of building materials, only the direct, or zeroeth-order inputs and associated outputs are considered. For example, when determining the environmental impacts associated with a tonne of steel, the burdens related to the manufacture of the mill's machinery were not considered; when calculating transportation effects, only the fuel used was included in the LCA profile, not the indirect or secondary impacts associated with the manufacture of the vehicle. In order to fully account for all embodied environmental effects of a building material, it is necessary to perform an economic input-output (EIO) analysis of the entire economy. Harvey (2006, p. 488) states that "to rely entirely on a process based approach will underestimate the true embodied energy [and subsequent environmental burdens], since interactions beyond some relatively low order will be omitted (that is, there is a truncation error)". The LCI data that was obtained from sources such as the US LCI, ASMI, and BEES<sup>®</sup> 4.0 was developed using a process-based analysis; although the truncation criteria was not provided and likely varied between data sets. Due to the nature of the process-based LCA calculation methodology, the absolute values of the LCIA results for both the concrete and timber building cases are expected to be lower than if an EIO based methodology was used. A comparative Australian study of a concrete- and wood-framed building demonstrated that indeed the process-based LCA methodology underestimated the absolute value of the energy requirements and GHG emissions by a factor of two, when compared to an EIO approach, but the final results of the comparative study remained the same regardless of the methodological approach; the concrete-framed building caused higher emissions (Lenzen & Treloar, 2002). It would be expected that the cradle-to-gate environmental impacts of Discovery Place - Building 12 would increase in absolute value if an EIO approach was used but the comparative results of the study would not be expected to change.

# 4.0 – DISCUSSION

# 4.1 – Interpretation of Study Results

## 4.1.1 – LCA of Wood Products: Manufacture and Carbon Analysis

The LCA model for CLT was developed using primary manufacturing data from a pilot scale CLT production facility; CST Innovations Limited, in New Westminster, B.C. There are considerable environmental and economic advantages when moving from pilot plant to full-scale production capability. This is usually realized through lower unit costs and lower environmental burdens per unit. Although there are many dissimilar underlying assumptions in the cradle-to-gate GWP comparison of European and North American manufactured CLT (refer to Table 9), there is a noticeable trend that during the manufacturing life cycle stage, full-scale production facilities produce CLT panels with lower GWP (refer to Table 8). The GWP comparison of the manufacturing life cycle stage of European and Canadian CLT, along with the inherent inverse relationship between production capacity and environmental impact (economy of scale) demonstrates that by using pilot-plant scale data for CLT production, the LCA study results are conservative in nature. Due to the large volume of the CLT used in the timber design scenario, the GWP environmental impact category and likely other impact categories of the timber building design case are hypothesized to be somewhat less if LCI input data from a full-scale North American CLT production facility were to have been used in this research project.

The use of different types of structural adhesives (PRF versus PU), which are employed to face bond the adjacent ply layers of CLT panels, as well as the lamellas of glulam beams and columns, was considered at the outset of the study. LCI data sets relating to North American and European-made PRF glue were available, as this product had been used extensively on both continents for the past three decades. PU, on the other hand, is relatively new to both the European and North American markets and at present, there exists no publically available LCI data for this product, therefore it was impossible to compare EWPs made with either PRF or PU on an environmental basis. The fossil fuel feedstock and the intensive manufacturing processes that are required for the

production of both PRF (Wilson, 2010) and PU adhesives, in conjunction with the fact that a cold setting PRF adhesive was modelled in the study, led to the conclusion that the application of PRF adhesive was both suitable and conservative in the North American context. Despite the fact that both PRF and PU have considerable environmental effects when considered alone on a per kilogram basis, only a low volume of either PRF or PU adhesive is required to produce a large volume of laminated timber. For this reason, the substitution of PU for PRF in the CLT and glulam structural applications is not anticipated to change the overall study results significantly and may possibly improve the environmental performance of the heavy timber-framed design scenario.

Through the carbon analysis wood products, it is important to outline the inclusions and exclusions that were taken into account when determining the net carbon consequence and GWP of biomass based building products. There are three defined ways in which wood products have the ability to contribute to climate change mitigation, as outlined by Werner et al. (2006, p. 319):

"They act as a carbon pool during their service lives, as they withdraw  $CO_2$  from its natural cycle...furthermore, wood products can substitute for more energyintense products...after their service life, they can substitute for fossil fuels if they are incinerated..."

This study follows the carbon accounting guidelines set out by the USEPA and the IPCC (2006), which consider any GHG emissions generated by the combustion of biomass based material to be carbon neutral. Therefore, any environmental impact generated from a biomass source, such as hog fuel or wood residues combusted in a sawmill, will not appear in the GWP impact category. The accounting legitimacy and scientific basis for considering the combustion emissions from biomass products as climate impact neutral is currently under debate (Searchinger et al., 2009), but will not be discussed further, as it is outside the scope of this study. The environmental impact categories and were accounted for as renewable embodied energy. The potential energy contained within the building's structure and envelope, such as wood framing, EWPs and other bio-based

building products, are considered feedstock energy sources in the embodied energy accounting method. The carbon stored in EWPs was accounted for as a negative value in the GWP category. Carbon storage of wood varies by species and density but is generally considered to be 1.84 kg of CO<sub>2</sub> per kg of harvested, oven-dry wood (Lippiatt, 2007). In order to be relatively precise and conservative in the estimate of carbon stored in the wood products contained within the two design scenarios of Discovery Place – Building 12, the density of CLT, glulam and framing lumber was taken as  $409 \text{ kg/m}^3$ .

The carbon savings that was possible by substituting biomass based energy sources for fossil fuel based sources during the production of building materials, was not calculated or reflected in the environmental impacts or the numerical energy accounting results. There was no GHG displacement factor applied or any credit given, with respect to either environmental impact or embodied energy, for the use of timber products over other more energy intensive substitutes (e.g. wood studs vs. steel studs). It was viewed as conservative to refrain from utilizing displacement factors when accounting for the substitution of building materials or renewable for non-renewable energy sources. Due to the lack of availability, combined with the variability of displacement factor magnitudes, it was viewed as an unsuitable environmental impact quantification metric, that risked increasing the underlying complexity of the study without offering any added precision. Finally, the end-of-life scenarios of bio-based wood products were not quantitatively calculated, with respect to carbon and energy implications, as this life cycle stage fell outside the cradle-to-gate study boundary. The subsequent sensitivity analysis (Section 4.2.4) aims to qualitatively interpret and understand how the LCA results would change, if indeed, end-of-life scenarios of wood products were taken into consideration.

### 4.1.2 – Building Design

Despite the fact that at the present time, bluestained MPB-killed timber is not allowed to be used in the manufacture of glued laminated timber, there is some research that shows it may be possible to maintain structural performance characteristics and the visual aesthetic of non-infected wood, in glulam column applications. Lam et al. (2006) have tested the performance (compression parallel to grain and MOE) of sixty 152 by 152

mm glued-laminated MPB bluestained lodgepole pine posts. In this study, the results showed that it was possible to obtain acceptable appearance and adequate structural performance characteristics. Although the glulam beam and column redesign of Discovery Place assumed the use of non-infected spruce, lodgepole pine and jack pine, it was conceivable to postulate, based on the research findings by Lam et al. (2006), that it was possible to also incorporate MPB-killed lodgepole pine lumber in glulam column structural applications of Discovery Place – Building 12.

The specified concrete strengths in the concrete building design case were modelled using lower compressive strength values than were defined on the structural drawings. For instance the concrete beams were specified as f'c = 30 MPa, yet were modelled in BEES<sup>®</sup> 4.0 as f'c = 28 MPa. The reason for this alteration was due to lack of LCI data contained in the USEPA database. These estimates were considered very conservative with respect to the concrete-frame design scenario, as compressive strength and environmental impact are directly related; that is if the concrete strength is increased, more cement powder is required and the environmental impact rises in every category. Therefore, the actual environmental burdens of the concrete-framed design scenario would have been greater if the specified concrete strengths were able to have been modelled exactly.

As mentioned in Section 2.5.1, the laminated-timber design scenario calculations were carried out using only the governing critical loading scenarios and then extrapolating these member sizes to other, less stringent loading situations. This one-size-fits-all, non-rigorous design approach was followed primarily due to time and manpower constraints, as well as to ensure the timber-framed design complied with and exceeded the current structural design codes and guidelines. It would have been possible to reduce the volume of wood contained in the timber design scenario, if in fact; additional iterations and case-by-case design calculations had been performed. Furthermore, the timber-framed design of Discovery Place – Building 12 was modelled and designed using identical plan and elevation layouts as its concrete-framed office building would most likely take on a different plan layout than was assumed in this project. The optimal timber-framed layout would be driven by the inherent material

performance properties of both glulam and CLT, as well as by economic considerations. The optimized laminated timber-framed design may not have included interior and spandrel beam spans, in addition to more load-bearing interior CLT walls and continuous multi-span CLT floor plates. These layout changes would all have an influence on reducing the volume of timber required in the building, in particular, the depths of the glulam beams and the CLT floor plates, as well as potentially reducing the cross-sectional area of the glulam columns. The economics of an optimal plan and elevation layout for the heavy timber-framed structure would most likely be dictated by the relative cost of glulam beams and columns versus CLT floors and walls. In this study, it was considered unnecessary to develop and design an optimal plan and elevation layout for the building design scenarios. It was decided to maintain the same building layout in both the concrete and heavy timber design scenarios, as this ensured the building users would obtain equivalent functionality and space usage; regardless of the difference in the structural building systems.

Although a number of different design criteria were considered in the heavy timber redesign of Discovery Place – Building 12, it was not possible to determine, either from existing North American construction examples or through calculation methodology, a guaranteed minimum level of performance with respect to various other design drivers. Fire protection and modes of possible collapse, acoustic performance, sound attenuation and vibration issues, as well as addressing building durability, longevity and service life considerations were some of the design provisions that were unable to be numerically quantified in the heavy timber design scenario.

In North America, the fire resistance and performance characteristics of glulam beams and columns is quite well understood and explicitly defined in design codes, whereas these properties are not yet formulated for North American manufactured CLT. Although there is a considerable amount of contemporary research related to fire performance of European-made CLT (Frangi et al., 2008; Frangi et al., 2009; Friquin et al., 2010), there are currently no fire performance guidelines for Canadian-made CLT panels. Frangi et al. (2008, p. 8) performed a natural full-scale fire test on a three storey CLT structure and determined "with pure structural measures it is possible to limit the

fire spread to one room...in the room above the fire compartment no elevated temperatures were measured and no smoke was observed" and that "by protecting the timber structure with gypsum plasterboards the damage of the Xlam solid timber panels was relatively small". Based on the European research results and the number of midrise timber-framed buildings constructed throughout the EU, the fire performance characteristics of the heavy timber-framed building design, assuming all walls were overlaid with gypsum plasterboard, was taken to be sufficient to meet Provincial fire code design standards.

With respect to serviceability requirements such as acoustic performance, sound attenuation and vibration issues, it was again difficult to measure these elements in the timber redesign, as there were no defined Canadian guidelines for these design concerns. In some European CLT details, sound and vibration transmission are controlled by using dampers (thin foam padding) laid in between the floor to wall and wall to wall CLT panel joints. Although Reichelt et al. (2009, p. 1347) demonstrated that "the application of tuned mass dampers is effective in reducing the vibrations of wooden floors", the comparative LCA study of Discovery Place – Building 12 did not include the use of dampers to control sound or vibrations. EU CLT manufacturers considered vibration to be adequately controlled when deflection is limited to 1/400 of the span length under UDL. Canadian design requirements for vibration control are applicable for light-frame floor assemblies only and limit deflection under a moving point load of 1 kN. Due to the lack of widely established North American guidelines specific to CLT assemblies, vibration control was unable to be checked numerically.

Due to the fact that CLT construction is a relatively new building technique, in Europe as well as North America, it was impossible to find construction of this type built before the mid-1990s. With the lack of existing examples, it was difficult to assess the relative durability of the heavy timber-framed design alternative. Ancient wood-framed structures, in excess of 500 years old, still exist today in places like Japan and China. As long as moisture ingress is controlled, through proper detailing of the building envelope and a maintenance regime was upheld, it was assumed that the timber design scenario would be just as durable as its concrete-framed counterpart. The option of using preservative treated wood, for applications that were susceptible to moisture penetration

was something that was considered but determined to be an unnecessary inclusion in the timber redesign of Discovery Place – Building 12.

### 4.1.3 – EE and GWP: Analysis and Literature Comparison

Table 10 illustrates the embodied energy (EE) and global warming potential (GWP) results for Discovery Place – Building 12, as compared to other North American specific LCA studies that were performed on commercial building structures over the past two decades. Refer to Section 1.4 – Literature Review for more detailed information regarding the LCA studies cited in the following table.

	<b>Embodied Energy</b> $(CUm^2)$	$\frac{GWP}{(ka CO a a (m^2))}$
Reinforced Concrete Frame	(GJ/m)	$(kg CO_2 eq./m)$
Cole (1994)	4.93	_
Hood (1995)	4.26	_
Cole & Kernan (1996)	4.79	-
Kernan (1996)	4.03	-
CWC (1997)	1.38	287
Guggemos & Horvath (2005)	8.30	550
Krogmann et al. (2008; 2009)	17.9	844
Robertson (2011) – This Study	4.60 <sup>F&amp;P</sup> /3.51 <sup>P</sup>	420
Timber Frame		
Marcea & Lau (1992)	0.74	40.7
Cole & Kernan (1996)	4.54	-
CWC (1997)	0.81	159
Gustavsson et al. (2010)	3.51	89.0*
Robertson (2011) – This Study	8.17 <sup>F&amp;P</sup> /3.49 <sup>P</sup>	126*
Structural Steel Frame		
Marcea & Lau (1992)	2.08	127
Cole & Kernan (1996)	5.13	-
CWC (1997)	1.94	230
Scheuer et al. (2003)	7.00	573
Guggemos & Horvath (2005)	9.50	620

Table 10 - Comparison of Study Results to Existing Whole-Building LCA Literature

\*Carbon storage of wood is considered as a credit (i.e. negative) F&P = Feedstock & process energy incl.

P = Process energy only incl.

As the above results dictate, it is often difficult to compare one LCA study to another. Although all the values listed in Table 10 had a cradle-to-gate boundary condition, each one used a different size and height case study building, altered or expanded LCI building material input data, as well as utilizing either a process-based LCA, an EIO model or a combination of both. These variations, in addition to differences in energy accounting (inclusion or exclusion of feedstock energy) and environmental modeling rationale, will cause skewing across studies and lead to a degree of incomparability between LCA study results. The first result that can be demonstrated from Table 10 is that the LCA results for Discovery Place – Building 12 were similar, within the same order of magnitude with respect to embodied energy and GWP, to all other relevant LCA studies. Throughout all the studies, it is clear that there is an overarching trend demonstrating that timber-framed buildings generally have a lower GWP than concrete and steel structures. A trend relating embodied energy (EE) and structural configuration was less discernable, especially when you attempt to analyze the results from this study, whereby the EE of the laminated timber building exceeded that of the reinforced concrete design.

When considering both feedstock and process energy, the EE associated with the heavy timber-framed design of Discovery Place – Building 12 exceeded the EE of the reinforced concrete scenario by a factor of 1.78 or almost 80%. At the outset of this research project, this result was not anticipated, as many past LCA studies have demonstrated wood-framed structures to have lower EE than concrete or steel alternatives, as shown in Table 10. It is important to note that none of the contemporary LCA studies considered the use of laminated timber (glulam and CLT) in a five-storey, non-residential application. Most other comparative LCA studies, such as Marcea & Lau (1992), Cole & Kernan (1996) have employed light wood-frame construction techniques when designing a mid-rise timber building (although the CWC (1997) study used a combination of exterior stud walls, wood I-joists and glulam members). The difference in EE between the concrete and timber cases of Discovery Place can be directly tracked to the volume and corresponding EE content of the laminated EWPs used in the heavy timber design scenario. The total volume of laminated timber (glulam and CLT) used in the redesign of Discovery Place – Building 12 was 4,147 m<sup>3</sup>, accounting for 88% of the

feedstock energy (Figure 45), but only 33% of the process energy (Figure 46) in the timber design scenario. Comparatively, the amount of concrete that was required in the above-grade portion of the reinforced concrete building design was 4,243 m<sup>3</sup> (refer to Table 7); demonstrating that less wood material was used in the timber redesign of the superstructure than in the original concrete-framed case.

The difference in material required for the superstructure of the concrete and timber designs can be realized by the fact that neither column drop panels nor slab bands were required in the timber design. In a concrete frame, drop panels are often required to resist punching shear forces that occur at the column and slab interface, whereas slab bands are wide, shallow concrete beams that resist bending forces. Neither of these elements were present in the timber design, which accounted for 475  $m^3$  of concrete. The reduction in cross-sectional area of the glulam columns and thickness of the CLT loadbearing walls in the timber design also resulted in a reduced volume of timber compared to concrete. There was a large difference in the volume of glulam beams (947  $m^3$ ) versus concrete beams (166  $m^3$ ), which was justified by the fact that the glulam beams were required to be much deeper, governed by design code requirements for vertical deflection. It was expected that less material volume would be required in the superstructure of the timber design case, as the building weight was greatly reduced by using wood instead of reinforced concrete, but it was not expected that less material would result in greater EE. Although laminated timber appears to contain more EE than an equivalent volume of reinforced concrete, the origins and accounting principles associated with the EE calculation need to be well understood.

When calculating the EE of laminated timber products, it is important to differentiate between process and feedstock energy. Process energy accounts for the amount of energy that was released when fuels are utilized or combusted during the production or operation of an industrial process (i.e. burning fossil fuels to operate a factory or a truck). Feedstock energy is the potential energy contained in fuel resources that are extracted from the Earth; such as the potential energy contained in bio-based EWPs or the natural gas feedstock contained within the molecular structure of the fossil fuel based wood adhesives. Comparing the feedstock energy of the concrete and timberframed designs, we can see that the timber design has over five times more feedstock

energy than the concrete design scenario (refer to Figure 44). This is due to the fact that the timber elements within the building store potential energy contained within the wood fibre (bio-based wood products accounted for 88% of the feedstock energy) and within the fossil fuel-derived chemicals used in the manufacture of the adhesive resins. The high amount of feedstock energy is an indicator that both the CLT and glulam products can be readily combusted and utilized as energy sources, after their useful lives. In the case of reinforced concrete, incineration is not practical or commonplace, making it difficult to easily obtain useful energy at the end of its service life. This is not to say that the reinforced concrete does not store potential energy; it does, as all matter stores energy, but it does not store readily accessible energy that can be easily extracted at the end of its service life. There was very little energy allocated to the feedstock category of concrete because it does not contain, within the final product, fuel inputs that come directly from the Earth (such as fossil or bio-based fuels). Almost all the energy used to produce concrete appears in the process energy category. Fuel inputs from the Earth are used in the production of concrete (i.e. natural gas to heat the cement kiln) but are not present within the final material product. In the case of this LCA study, the higher content of feedstock energy in the heavy timber design alternative is not indicative of an environmentally inferior material selection but instead demonstrates that there is a larger amount of easily accessible potential energy contained in the timber design than the concrete design.

With respect to process energy, there was relatively no difference between the concrete- and timber-framed alternatives (refer to Figure 44); meaning that approximately the same amount of energy was released throughout the production and operation of the industrial processes associated with the manufacture of the building materials in both design scenarios. This finding becomes more interesting when it is combined with the energy accounting of fuels based on their renewability (refer to Figure 43). The concrete building attained 20% of its EE from renewable sources, whereas in the case of the heavy timber-framed building, renewables accounted for over 60% of the total EE. With respect to the absolute value of non-renewable EE, the amount associated with the concrete design case was greater than the timber case by almost seven terajoules. Knowing this, when we now look at the fact that the concrete and timber-framed

buildings use the same amount of process energy ( $\sim 3.5 \text{ GJ/m}^2$ ), it is reasonable to ascertain that a much higher percentage of this process energy was derived from renewables, in the case of the timber building, when compared to the reinforced concrete design. It is possible and would have been advantageous to determine the numerical value of fuel renewability associated with process energy (e.g. how much of the process energy was associated with renewable sources; such as the combustion of biofuels for heat energy?), unfortunately a detailed comparison of this sort was not possible, as all of the building material LCI data sets were not aggregated in such a manner. The comparative values of fuel renewability also indicated that despite the timber-framed building having more associated cumulative EE, much more of this energy was derived from renewable sources. In addition, the absolute value of non-renewables was calculated to be 14% less than the concrete building design case. Recalling that the timber building design demonstrated superior environmental performance in all but one impact category, yet demonstrated a much higher cradle-to-gate embodied energy total (feedstock plus process), it became apparent that in the case of this particular LCA study, it was not accurate to directly correlate embodied energy results with environmental impacts; a conclusion that echoes the work done by Svensson et al. (2006).

The total volume of wood contained in the heavy timber design scenario was approximately 4,161 m<sup>3</sup>, which stored roughly 3,131 tonnes of carbon dioxide equivalent within the building structure and envelope makeup. If the carbon storage property of wood was not included in the GWP calculation, the total amount of  $CO_2$  equivalent associated with the cradle-to-gate emissions analysis would have been 4,930 tonnes, still over a kilotonne less than the reinforced concrete alternative. When considering GHG emissions, the heavy timber design alternative outperformed the concrete-framed counterpart by over 70%, when taking into account carbon storage and by 17%, even when the carbon storage property of wood was not considered. As was stated in Section 4.1.1; any GHGs generated from a biomass source, such as wood residues combusted for drying lumber, are considered impact neutral will not appear in the GWP impact category. Although the exact value was not possible to calculate (due to lack of LCI data aggregation), it would be interesting to determine the net carbon balance of the timber-framed building; that is, how much  $CO_2$  equivalent (including emissions resulting from

the combustion of biomass) was associated with the cradle-to-gate production of the heavy timber-framed building materials, compared to the 3.1 kilotonnes of  $CO_2$  equivalent stored within the building fabric?

# 4.1.4 – Building Enclosure Comparison

The building enclosure (also known as the building envelope) of Discovery Place - Building 12 consisted of three different weather and wind resisting elements; a built-up exterior wall assembly, a curtain wall system (visual glazing and thermally insulated spandrel glazing elements), and a built-up roofing system, as well as operable fenestration elements such as pedestrian and vehicular access doors. The timber redesign focused on substituting, where feasible, timber elements into the built-up exterior wall and roof make-ups, as well as redesigning the spandrel section of the curtain wall system. The building enclosure redesign aimed to incorporate timber elements, as well as altering the thicknesses or removing individual elements, in order to obtain a timber enclosure design that maintained the original heat resistance (RSI) of the concrete-framed wall and roof assemblies. The RSI value was allowed to vary within only three percent in both the concrete- and timber-framed design scenarios, in order to ensure a functionally equivalent building comparison; whereby each design alternative would have almost identical operational energy use characteristics over the 50-year study lifetime. It was also decided that the window-to-wall ratio (~65%) would be conserved in each case, ensuring identical passive solar performance. Although the exterior cladding elements were altered, in both colour and texture, the conservation of the window-to-wall ratio throughout each design scenario also attempted to preserve the aesthetic architectural form and appearance of the façades in both the concrete- and timber-framed designs.

The exterior wall and roof assemblies, along with the spandrel glazing section contained within the curtain wall system are compared for both the concrete and timber design alternatives in Table 11, as follows:

### Table 11 – Design Comparison of Exterior Wall, Roof and Spandrel Glazing Assemblies

Concrete Design	Timber Design	
Exterior Wall Assembly		
Outdoor air	Outdoor air	
203 mm reinforced concrete wall	13mm generic cedar siding	
13 mm airspace	6 mm vapour permeable membrane	
92 mm steel studs @ 400 mm O/C	165  mm (5-nly)  CI T wall	
64 mm ccSPF insulation	12 mm auroum well board	
13 mm gypsum wall board	1.3 mm gypsum wall board	
Indoor air	Indoor air	
Wall Assembly Thickness = 321 mm	Wall Assembly Thickness = 196 mm	
$RSI = 1.56 \ m^2 K/W$	$RSI = 1.57 \ m^2 K/W$	
Flat Roof Assembly		
Outdoor air	Outdoor air	
2-ply SBS membrane	2-ply SBS membrane	
76 mm R-12 rigid insulation	32 mm R-12 rigid insulation	
6 mm vapour barrier	6 mm vapour barrier	
229 mm reinforced concrete slab	00, 165, 221 or $207$ mm (2, 5, 7, or 0, rky) CLT result	
64 mm ccSPF insulation	99, 103, 231 of 297 mm (3-, 3-, 7- of 9-piy) CL1 panel	
Indoor air	Indoor air	
Roof Assembly Thickness = ~381 mm	Average Roof Assembly Thickness = ~321 mm	
$RSI = 2.68 \ m^2 K/W$	$RSI = 2.70 \ m^2 K/W$	
Curtain Wall Assembly – incl. Spandrel Glazing		
Outdoor air	Outdoor air	
6 mm spandrel glass	6 mm spandrel glass	
67 mm air space	92 mm air space	
25 mm R-12 semi-rigid insulation	19 mm R-12 semi-rigid insulation	
92 mm steel studs @ 610 mm O/C	38 x 89 mm wood studs @ 610 mm O/C	
13 mm gypsum wall board	13 mm gypsum wall board	
Indoor air	Indoor air	
Spandrel Assembly Thickness = ~203 mm	Spandrel Assembly Thickness = ~219 mm	
Curtain Wall Assembly $RSI = 1.38 m^2 K/W$	Curtain Wall Assembly $RSI = 1.39 \text{ m}^2 \text{K/W}$	

When comparing the exterior wall and roof assemblies of the concrete- and heavy timber-framed building designs, it was clearly demonstrated that equivalent RSI values were reached in the heavy timber design by using wall and floor make-ups that were considerably thinner than in the reinforced concrete design. This was shown explicitly in the exterior wall and flat roof assemblies, with the timber design yielding reductions in

thickness of 125 and 60 mm, respectively. This efficiency was realized through the superior heat resistance value of solid timber elements over reinforced concrete walls and slabs. The tubular nature of wood at the microscopic level allows it to trap still air within its cellular structure, giving the solid timber elements their ability to resist temperature gradients more effectively than a concrete wall of identical thickness. In turn, this improvement in material RSI value allowed for reduction and in some cases complete removal of insulation material that was required; as was the case in the exterior wall and roof assemblies, whereby the ccSPF insulation was no longer required in the heavy timber design in order to reach an RSI value that was equivalent to the original concrete design. In the case of the flat roof assembly, the thickness of the R-12 rigid insulation was also reduced by over 50%, while still achieving an RSI value that was slightly higher than the concrete roof make-up. The two elements that were changed in the timber redesign of the spandrel glazing section of the curtain wall assembly was the substitution of wood studs for steel studs, which in turn allowed for the removal 6 mm of the R-12 rigid insulation. This reduction of insulation material required a slight addition of wall thickness for an extra 25 mm air space, while increasing the RSI value of the spandrel wall panels slightly in the timber design.

The exercise of redesigning the building enclosure of Discovery Place – Building 12 demonstrated that indeed it was possible to devise highly efficient wall and roof assemblies using solid timber CLT elements as both vertical walls and horizontal floor plates. The extraordinary heat resistance properties of CLT panels allowed for large reductions in wall and floor thicknesses, as well as extensive material savings, most prominently in rigid and ccSPF insulations. The building enclosure designs that were devised for Discovery Place were required to match and maintain functional equivalency with respect to the original RSI values of the concrete-framed building. In reality, a redesign application would not consider equivalent lifetime energy use but would strive for lower lifetime energy use through more effective, insulated building enclosures. In these instances, it would be logical to take full advantage of the high heat resistance properties of CLT elements and use this as a basis to design and construct building enclosure assemblies that reach far beyond the current North American best practices and energy efficiency standards.

# 4.2 – Sensitivity Analysis: Inputs and Boundary Conditions

The following sections grapple with expansions, changes and modifications to the cradle-to-gate LCA input parameters and system boundary conditions. The sensitivity analysis attempted to determine the significance of input variables and system boundary selections, through both quantitative and qualitative investigation; it "is a procedure to determine how changes in data and methodological choices affect the results of the LCIA" (CAN/CSA-ISO 14044, 2006). The first segments (Sections 4.2.1 & 4.2.2) undertook a quantitative approach to sensitivity, whereby input variables were changed, LCIA results were calculated (based on the new inputs) and these results were then compared to the baseline results derived in the main body of the report. The quantitative sensitivity analysis section was an iterative procedure that attempted to showcase the validity and robustness of the comparative LCA results of Discovery Place – Building 12.

In addition to the exclusively numerical examination procedure, as described above, the subsequent sensitivity analyses (Sections 4.2.3 & 4.2.4) were a combination of quantitative and qualitative in nature. They attempted to shed light on the effects of the inclusion of alternative life cycle stages and boundary condition decisions. The consideration of the environmental and energy use impacts associated with the on-site construction and end-of-life stages, as they related to the case study building design scenarios was discussed in an effort to expand the comprehensiveness of the LCA study and seek to determine how the inclusion or exclusion of life cycle stages may have affected the comparative LCA results.

# 4.2.1 – Lower Impact Concrete Mix: A 5% Increase in Fly Ash Content

Supplementary cementing materials (SCMs) are waste products that are used as substitutes for portland cement when making concrete. Common SCMs include blast furnace slag and fly ash, which are waste products from steel production and coal-fired power plants, respectively. Silica fume and limestone are also used as SCMs. This sensitivity analysis will focus on the use of fly ash; a waste material that is left over when coal is burned to generate electricity. "In LCA terms, fly ash is an environmental outflow of coal combustion, and an environmental inflow of concrete production. This waste
products is assumed to be an environmentally "free" input material...The environmental burdens associated with the production of waste materials are typically allocated to the intended product(s) of the process from which the waste results." (Lippiatt, 2007). Therefore, when fly ash was considered in the LCA of Discovery Place – Building 12, the only direct environmental burdens associated with it were derived from the transportation of the product from the coal-fired generating station to the concrete ready mix plant.

The original LCA input data for concrete production had assumed a 15% fly ash content in the concrete mix for both the concrete and laminated timber design scenarios. The reasoning behind this assumption stemmed from the LEED<sup>®</sup> platinum green building certification of Discovery Place – Building 12. Obtaining LEED<sup>®</sup> platinum most likely required the designers and specifiers to use SCMs in the concrete mix, in order to obtain the LEED<sup>®</sup> credits 4.1 and 4.2 under the Materials and Resources section of LEED<sup>®</sup> Canada Core and Shell rating system. These credits require that a minimum of 10% and 20% recycled content must be contained in the building materials used for the project. Therefore an average of 15% recycled fly ash was assumed in the concrete mix. The sensitivity analysis increased the percentage of fly ash in the concrete mix from 15% to 20% in both the concrete- and heavy timber-framed building design scenarios. The comparative LCA results using a 20% fly ash concrete mixture are shown in Figure 47.



Figure 47 – Comparative LCA Results Using 20% Fly Ash Concrete Mix

The sensitivity analysis related to increasing the fly ash content to 20% in the concrete mixes for both the reinforced concrete- and laminated timber-framed buildings yielded results that were almost identical to the original LCA impacts, which used a 15% fly ash concrete mix. Only four impact categories recorded an improvement of 1–2% with respect to the concrete-framed design over the heavy timber design; these being global warming, smog formation, eutrophication, and fossil fuel depletion potentials, whereas all other environmental impact categories remained unchanged. With respect to total embodied energy, both the concrete and timber designs saw a reduction of approximately 1% in the cumulative embodied energy of construction materials.

These sensitivity results demonstrated that a simple alteration of the concrete mix, by adding 5% more fly ash, led to a 1–2% relative improvement of the reinforced concrete design over the timber design in four of eleven environmental impact categories. It was anticipated that adding more fly ash would have had a much greater impact on improving the environmental and embodied energy performance of the concrete-framed building over the timber-frame due to the fact that the concrete building contained a much higher volume of reinforced concrete structure than the heavy timber design.

Nonetheless, this result indicated that the effect of using a concrete mix containing higher fly ash content did not significantly reduce the environmental impacts of the concreteframed building relative to the heavy timber design. The 20% fly ash content aided in marginally decreasing the environmental and energy impacts of both building design scenarios but was not a major catalyst in reducing the environmental effects of the reinforced concrete design over the laminated timber design.

### 4.2.2 – Laminated Timber Material Quantities: A Variation of ± 10%

The heavy timber redesign of Discovery Place – Building 12 was based on material design properties for CLT that were developed through mechanical testing of sample specimens (Chen, 2009; 2011). The design properties that were calculated are based on bending tests from a small sample size of CLT panels that were considerably smaller in length, width, and depth than typical CLT elements that would have been specified in the construction of a mid-rise, five-storey office building such as Discovery Place – Building 12. In addition to the CLT design criteria considerations, the structural design process of the timber building consisted of determining worst case loading scenarios for the CLT floor plates and walls, as well as the glulam beams and columns. These worst case scenarios were then used to design structural members that were subsequently used for all other, less stringent, loading situations. When considering these two limitations in the design process, it is valid to conclude that through further material testing of CLT floor and wall elements, along with increasing the number of design iterations and situational arrangements, it would be possible to "tighten up" the structural design of Discovery Place – Building 12. With enhanced mechanical testing regimes and greater sample sizes related to material performance characteristics of both the horizontal and vertical CLT elements, more accurate structural design properties could be established. It is not yet known how alternate material testing, sample size variation and the resulting changes in design values would affect the material quantity of CLT in the timber building design scenario. On the other hand, performing an increased number of structural design calculation iterations (using the values contained in Table 1 and CAN/CSA-O86-01), on both the CLT and glulam elements, would most likely result in a

decrease of the volume of timber required to meet the minimum structural code performance requirements. Therefore, with the implementation of these two design changes (more accurate CLT design criteria and augmented structural design iterations); it is unclear as to what the net effect would be on the volume of laminated timber contained within the heavy timber-framed design alternative of Discovery Place – Building 12. In order to encapsulate both extremes of the laminated timber material quantity outcome, a variance of  $\pm$  10%, when compared to the bill of materials listed in Table 7, was applied to the material quantities of both CLT and glulam in the heavy timber design scenario. The outcomes of the sensitivity analysis that increased and decreased the laminated timber quantities by 10% are shown as Figures 48 and 49.



Figure 48 – Comparative LCA Results for a 10% Increase in Laminated Timber Volume

Increasing the volume of laminated timber (CLT and glulam) in the heavy timber design scenario yielded results that were predominantly advantageous to the concrete design, although not in every impact category. With an increase of 10% laminated timber, the reinforced concrete building became a less environmentally detrimental option in all impact categories except three; global warming potential, human health effects, and ozone depletion potential. With the addition of 10% more laminated timber in the wood-framed design, the environmental performance of the timber building decreased from a minimum of less than 1% up to a maximum of 4%, relative to the reinforced concrete design. The most prevalent effect was recorded in the fossil fuel depletion impact category, which measured a 4% decline in the relative environmental performance of the laminated timber design, with most other categories showing a 1 or 2% variation. An interesting result that was also observed in this sensitivity analysis was the fact that the global warming potential of the timber building actually improved by 4% over the concrete-framed design, even with the addition of 10% more laminated timber to the building structure. This improvement was a result of the fact that when considering the carbon storage properties of wood, both glulam and CLT store more CO<sub>2</sub> equivalent than they release during their cradle-to-gate life cycles (refer to Figure 16). With respect to total embodied energy, the addition of 10% more laminated timber resulted in an increase of just over 6% or 7 terajoules of energy when compared to the cumulative embodied energy content of the original timber design scenario.



Figure 49 – Comparative LCA Results for a 10% Decrease in Laminated Timber Volume

The environmental impact and embodied energy results associated with a 10% decrease in laminated timber volume were the mirror image of the results obtained from a 10% increase in laminated timber. That is, with the subtraction of 10% of the laminated timber volume in the wood-framed design, the environmental performance of the timber building increased up to 4%, relative to the reinforced concrete design. The inverse relationship between additional laminated timber and global warming potential was maintained; with an increase of 4% in GWP being observed, despite 10% of the laminated timber being removed from the wood-framed design. With respect to total embodied energy, the subtraction of 10% of the laminated timber resulted in a decrease of just over 6% or 7 terajoules of energy when compared to the cumulative embodied energy content of the original timber design scenario.

### 4.2.3 – Inclusion of On-site Construction Stage in LCA Framework

The purpose of this section was to review, discuss, and estimate the relative environmental impacts associated with the on-site construction life cycle stage of both the concrete- and heavy timber-framed design scenarios. A literature review of contemporary research findings that related to the environmental impacts associated with the construction phase of North American, mid-rise office buildings was performed in order to apply previous findings to the design context of Discovery Place – Building 12. The goal of this sensitivity analysis was to look beyond the cradle-to-gate study boundaries and approximate, both quantitatively and qualitatively, the relative environmental and energy use differences that existed in the construction stage of the concrete- and heavy timber-framed design alternatives of a five-storey office building. The aim was also to determine how the expansion of the cradle-to-gate system boundary, to include the on-site construction phase, would affect the comparative LCA results profile of the concrete and heavy timber design alternatives. According to the Canadian-based study by Cole (1999, p. 335), there are five general categories that influence the environmental impacts and energy use of on-site construction:

- The transportation of the building crew to and from the construction site for the duration of their construction task;
- 2) The transportation of materials from a distribution centre to the construction site;
- The transportation of equipment specific to the construction task to and from a central depot to the building site;
- 4) The use of on-site equipment specific to the construction task;
- 5) Supporting processes such as form-work and temporary heating.

When considering all of the above influence factors relating to on-site construction impacts only, Cole (1999) found that with respect to construction energy use and related GHG emissions impacts per square metre of floor area, glulam structural frames (spans of 6.1–9.2 meters), overlaid with 50 mm tongue and groove decking, fell between 17–20  $MJ/m^2$  and 2.3–2.5 kg CO<sub>2</sub> eq./m<sup>2</sup>, whereas cast-in-place reinforced concrete walls (200– 300 mm thick), flat plate slabs and columns (spans of 6.1–9.2 meters) required the highest construction energy at  $90-120 \text{ MJ/m}^2$  and were responsible for the largest GHG emissions at 13–20 kg CO<sub>2</sub> eq./m<sup>2</sup> recorded in the study. Cole (1999, pp. 340-341) also remarked that "cast-in-place systems are among the highest [within the group of concrete structural systems that also included concrete block, precast and tilt-up construction] and entail greater energy in transporting workers to and from the building site (approximately 40–50% of the total)". Additional interesting findings that related to the LCA comparison of Discovery Place – Building 12 that were drawn from the Cole (1999, pp. 341-342) study included; a) "for glulam beams...energy use per  $m^2$  decreases with increased load...[and] decreases slightly to moderately with increased span" and b) "those systems requiring heavy on-site equipment (e.g. cranes) tend to show savings in energy use per square meter as size or load increases since the same energy is expended within the equipment's capacity, regardless of material size". Quantitatively, this LCA

study found that for glulam-framed assemblies, the construction energy, as a percentage of total embodied energy, ranged from 6–14% and GHG emissions as a percentage of initial embodied GHGs, ranged from 8–14%, whereas with cast-in-place concrete, the ranges for energy and GHG emissions were considerably higher at 13–25% and 15–25%, respectively. Steel-framed assemblies demonstrated the overall lowest energy and GHG emissions levels in the Cole (1999) study, being marginally lower than those of wood-framed construction systems, whereas concrete systems were generally an order of magnitude larger than both steel- and wood-framed structures, with respect to both construction energy and associated GHG emissions. In almost all construction assemblies, this study found that transportation of workers to and from the job site represented the largest portion of energy use during the on-site construction process.

Guggemos and Horvath (2005) also used LCA to analyze the environmental impacts resulting from the on-site construction phase of a mid-rise, five-storey office building in the Midwestern United States, constructed out of either reinforced concrete or structural steel. Their results did not include worker transportation to and from the job site and found that during the construction phase, the steel-framed building required about half of the energy (418 vs. 939  $MJ/m^2$ ) than the concrete-framed alternative, with heavy equipment contributing to the bulk of the energy use in both cases. Junnila et al. (2006, p. 15) also found that when the transportation of workers to and from the job site was not considered, "equipment use accounts for the majority of energy use and emissions in the construction stage" of a five-storey, concrete-framed office building in the U.S. This result was previously confirmed by Junnila & Horvath (2003, p. 161), whom analyzed a five-storey, reinforced concrete building in Finland and noted that "when the construction phase is examined separately, environmental impacts are primarily attributable to two elements – use of construction equipment and materials (...such as formwork, temporary structures and so on)". With respect to the entire building life cycle (materials, construction and end-of-life phases), Guggemos & Horvath (2005, p. 100) found that "construction phase impacts represent a relatively small part (0.4-11%) of the overall building life cycle energy use and emissions". In order to minimize the on-site construction phase impacts of a mid-rise office buildings, Guggemos & Horvath (2005, p. 100) specified the areas which would generate the largest

environmental and energy savings, including; "minimizing the amount of temporary materials used, including reusing temporary materials if possible...more prefabrication work and the use of standard sizes in design can also help". In a later publication, they also remarked that "prefabrication should be favoured over on-site fabrication due to higher productivity, reduced equipment use, and reduced waste generation" (Guggemos & Horvath, 2006, p. 194). Although not measured directly in their LCA study, Guggemos & Horvath (2005, p. 100) noted that "waste generation at the construction site is also of concern, particularly excess concrete materials".

Taking into consideration the above research findings directly related to the construction of mid-rise building systems, it was possible to extrapolate these to the comparative designs of the Discovery Place – Building 12 office structure. The first stark difference between the construction sequences of a five-storey concrete or heavy timber (glulam and CLT) structural system was the variation in the erection times. A reinforced concrete-frame required significantly more on-site time and manpower in order to build form-work, place rebar, pour concrete, allow time for curing and finally strip the forms. This was not the case with the heavy timber building design, as all glulam beams and columns, as well as CLT walls and floor plates are prefabricated off-site and arrive at the construction site cut to size, often with service openings pre-drilled and can be erected almost immediately after being lifted off the truck bed. As an example, according to TRADA Technology (2009), the Stadthaus, a nine-storey CLT apartment building in London, England was erected in 49 weeks with a mobile crane and no use of temporary scaffolding for the structure; taking a four man crew only 27 working days to erect the eight-storeys of CLT superstructure. It was estimated that an equivalent concrete structure would have taken 72 weeks to erect and required the use of a tower crane, temporary form-work and scaffolding. A second British example of CLT construction, Kingsdale School, expressed that "the use of cross-laminated timber panels offered many other advantages including improved on-site erection periods, sustainability, omission of wet trades and factory quality finishes" (TRADA Technology, 2008, p. 2). The Open Academy, a 9,000 m<sup>2</sup> school also located in the U.K., used CLT for 96% of the threestorey structure, with intermittent glulam beams, steel connectors and a slab-on-grade foundation. The erection schedule lasted 16 weeks, required 12 men, 83 deliveries, and

used two cranes without any scaffolding (Campbell, 2010). In addition to the rapid erection time, timber buildings require only simple power tools for drilling and coring when compared to the heavy equipment required for concrete or steel construction alternatives. The use of smaller construction equipment may well lead to a reduction in on-site electricity use, noise, and dust generation.

The Canadian study by Cole (1999) clearly demonstrated the lower energy use and GHG emissions associated with the construction of glulam-framed buildings over cast-in-place reinforced concrete structures. As well, extrapolating from Cole's results, glulam-framed buildings may have increased performance when considered in the midrise building context as energy use per square metre tended to decrease with increased load and span. Although, the cradle-to-gate analysis already included the transportation of materials from a distribution centre to the construction site, further energy and environmental savings could be realized in the timber design scenario through the use of smaller construction specific tools and equipment, the absence of temporary materials such as form-work and scaffolding and a shortened construction schedule, leading to less energy and emissions expended for workers travelling to and from the job site. Additionally, according to Guggemos & Horvath (2006), the notion of prefabrication in heavy timber construction, as it relates to glulam and CLT designs, provides an opportunity for higher construction efficiency and productivity, along with reduced equipment use and on-site waste generation.

Based on the literature review and the analysis of the construction schedule, manpower, equipment, and temporary materials requirements, it can be estimated that the construction of the heavy timber design alternative will most likely generate lower GHG emissions and use less energy during construction than its cast-in-place reinforced concrete counterpart. The quantitative value of exactly how much less of an effect the timber-framed design will have during the construction phase remains unclear, although results based on the work by Cole (1999) estimated that an improvement of four-fold with respect to GHG emission per square metre and eight-fold with respect to energy use per square metre may be plausible. It was not possible to gauge the relative changes that may occur in any other environmental impact categories, as previous studies had only focused on energy use and GHG emissions.

### 4.2.4 – End-of-life Choices, Implications and Future Considerations

Buildings will inevitably reach the end of their functional life cycle; whether the justifications for retirement are "changing land values, lack of suitability of the building for the current needs, lack of maintenance of various non-structural components" (O'Connor, 2004, p. 1) or structural failure beyond repair; end-of-life scenarios must be duly considered and addressed when taking into account a full life cycle agenda. The purpose of the following section was to review, discuss, and estimate the relative environmental impacts associated with the end-of-life stage of both the concrete- and heavy timber-framed design scenarios. A literature review of contemporary research findings that related to the environmental impacts associated with the end-of-life phase of mid-rise building constructions was performed in order to apply previous findings to the design context of Discovery Place – Building 12. The goal of this sensitivity analysis was to look beyond the cradle-to-gate study boundaries and to approximate, both quantitatively and qualitatively, the relative environmental impacts and energy use differences that existed at the end-of-life stage of the concrete- and timber-framed design alternatives. The aim was also to determine how the expansion of the cradle-to-gate system boundary, to include the end-of-life phase, would affect the comparative LCA results profile of the concrete and heavy timber design alternatives.

When examining the demolition of a five-storey, concrete-framed office building in the Midwestern United States, Junnila et al. (2006) found that the energy associated with demolition was just over 5% of both the total embodied energy and  $CO_2$  emissions, as well as 3%, 21%, and 7% of  $SO_2$ ,  $NO_x$ , and  $PM_{10}$  emissions, respectively. This study considered only the materials, construction, maintenance and demolition life cycle stages, omitting the building use phase from the analysis. Junnila et al. (2006, p. 15) assumed that all demolition waste was shipped to a landfill and noted that "the demolition equipment emissions are notable...in fact, it is slightly more than the energy use and emissions from equipment used in the construction stage".

Krogmann et al. (2008) performed a LCA of a newly constructed, highperformance educational building in New Jersey, utilizing the USEPA's BEES<sup>®</sup> 4.0 software. The 891 m<sup>2</sup>, reinforced concrete-framed institutional building, located on the Rutgers University campus, was considered over a 50-year lifetime and reported

demolition, decommissioning and transportation activities to have accounted for about 3% of primary energy consumption and between 2–4% of the environmental impacts (GWP, acidification, eutrophication and ozone depletion potentials), when considering all life cycle stages except the building use phase (Krogmann et al., 2008).

The decommissioning analysis of a six-storey, 7,300 m<sup>2</sup>, institutional building, located on the University of Michigan campus, reported demolition, decommissioning, and transportation activities to have accounted for about 8% of primary energy consumption and between 6–18% of the environmental impacts (GWP, ozone depletion and nutrification potential), with demolition waste accounting for 20% of the total waste generated when considering all life cycle stages except the building use phase (Scheuer et al., 2003). Although the building height and use was similar to Discovery Place – Building 12, the structural system of the University of Michigan building used steel columns, with a combination of concrete-topped steel deck and precast concrete floors.

Gustavsson et al. (2010) undertook a study to examine the life cycle energy use and GHG emissions associated with the material production, operation and demolition of the Limnologen; an eight-storey, heavy-timber framed apartment building located in Växjö, Sweden and constructed using both CLT and glulam structural elements. Quantitatively, the authors decided to use a conservative value from previous literature to account for the primary, fossil fuel derived energy required for the demolition activities  $(36 \text{ MJ/m}^2)$  and then added to this the fossil fuel energy required (most likely for transportation) to facilitate the recovery of the wood-based materials, for a total of 58  $MJ/m^2$ . The amount of energy stored within the wood demolition waste was -2.077 $MJ/m^2$ , giving a net balance of  $-2.020 MJ/m^2$ , when biomass energy recovery was employed. With respect to recovery rates, this study "assumed that 90% of the woodbased demolition materials are recovered and used as biofuel, with the remaining 10% of wood materials decaying into  $CO_2$  released to the atmosphere" (Gustavsson et al., 2010, p. 236). Gustavsson et al. (2010, p. 237) also remarked that "the energy used for demolition and recovery of wood-based materials is very small in relation to the heat energy content of the recovered demolition wood". The GHG emissions that were directly associated with the demolition activities was 3 kg  $CO_2/m^2$ , which equated to 1% of the total GHG emissions, when biomass recovery and the operational use phase are not considered. Some of the most interesting findings that were presented in this study were that "during the construction phase...more energy can be obtained from biomass residues from the wood products chain than is used to produce the building. Additional bioenergy can be obtained at the end of the building life cycle if wood-based demolition residues are recovered and used as biofuel" (Gustavsson et al., 2010, p. 240). There are several opportunities for generation of bio-based energy throughout the wood products chain, including logging and processing residues, as well as construction and demolition waste, as depicted graphically in the life cycle of bio-based building materials and products, as Figure 50.



Figure 50 - Life Cycle of Wood-based Building Materials (Gustavsson et al., 2006)

There are two relevant studies that compare the demolition energy intensity for either wood, steel or concrete buildings deconstructed in the North American perspective and environment. The National Trust for Historic Preservation (1981) suggests values of 27.1, 81.7 and 136.2  $MJ/m^2$  as the energy per area associated with the demolition of a 5,000 m<sup>2</sup> wood, steel or concrete building, respectively. Although these values are somewhat out-dated and do not specify the inclusion or exclusion of transportation burdens, they are useful in that they demonstrate a relative ranking for each of the major structural support systems.

A more recent comparative analysis of the demolition energy associated with the deconstruction of the structural frame of a  $4,620 \text{ m}^2$ , three-storey office building, located

in either Toronto or Vancouver, Canada was published by ASMI (1997). In this study, the wood structure was designed using glulam beams and columns, prefabricated engineered wood joist, plywood sheathed shear walls, and plywood floors, topped with concrete, whereas the concrete structure used cast-in-place reinforced concrete columns, shear walls, and flat plate slabs, with the roof slab containing slab bands. The wood and concrete construction systems contained in the ASMI (1997) study were both very similar to the alternative structural designs of Discovery Place – Building 12. This study also compared the relative merits of recycling and reusing the demolished building materials. Numerically, when considering recycling, the average energy intensities (averaged over location and summer/winter seasons) of the wood, steel, and concrete structures were as follows; 118, 110, and 103  $MJ/m^2$ . The wood and steel assemblies were highly sensitive to weather conditions, as they required a significant amount of manual labour to remove the concrete floor toppings, using pneumatic chipping hammers. According to ASMI (1997), if the concrete topping was not present in the wood structure, the demolition energy would have been reduced by almost 22%, to 93  $MJ/m^2$ . When considering the reuse option, the average energy per unit area was 92, 223, and 144  $MJ/m^2$  for the wood, steel, and concrete structures, respectively. The reason that the wood structure's demolition energy was the lowest with the reuse option under consideration was "due to the almost exclusive use of manual labour for all the above grade dismantling work" (ASMI, 1997, p. 63). The subsequent findings of relevance in the ASMI (1997, pp. 59-60) study included the notion that "the energy required for the demolition of the structural system is...significant relative to the initial embodied energy" and that "demolition for reuse requires more energy than demolition for recycling" and finally, "demolition performed predominantly by large machinery is less affected by weather and is also less energy intensive due to high efficiency".

The research related to the environmental effects and energy use associated with the demolition phase of a North American, mid-rise office building shows a consistent trend with respect to energy use, despite the numerical values being variable. The studies that compared wood, concrete, and steel building systems (National Trust for Historic Preservation, 1981; ASMI, 1997) found that wood-framed buildings consistently demonstrated the lowest demolition energy per unit area. There was evidence that

suggested the demolition energy use and GHG emissions were between 3–8% of the total embodied energy and emissions for both concrete- and steel-framed buildings (Junnila et al., 2006; Krogmann et al., 2008; Scheuer et al., 2003), whereas these values were only 1% for a heavy timber-framed building (Gustavsson et al., 2010); over a 50-year life cycle, when not accounting for biomass recovery and operational energy use. This evidence points to the conclusion that mid-rise, wood-framed office structures use less energy during the demolition phase, in conjunction with the demolition phase having a slightly lower relative impact on the overall life cycle energy use and GHG emissions profile. The concrete-framed design may have an advantage if demolition were to take place under inclement or winter weather conditions, as the use of heavy machinery is less affected by weather than manual labour. Considering overall impacts, if the demolition phase were to be included in the comparative LCA framework of Discovery Place – Building 12, the heavy timber design alternative would likely outperform the cast-inplace reinforced concrete design, when considering only energy use and GHG emissions. It was impossible to estimate any other relative environmental impacts, as there was no concise data that documented other impact indicators (SO<sub>2</sub>, NO<sub>x</sub>, PM<sub>10</sub>, etc.) related to the demolition of wood-framed buildings.

In addition to energy use and GHG emissions associated with the demolition phase of a building's life cycle, it is also prudent to discuss the disposal options that exist for both reinforced concrete- and heavy timber-framed structures. At the demolition phase, building materials can be recycled or reprocessed, reused, disposed of in a landfill or converted to useable energy. ASMI (1997) found that demolition time periods and energy requirements were generally higher when structural building materials were envisioned to be reused after the demolition process, as opposed to recycled. In reference to Discovery Place, the reuse option seems more feasible with the heavy timber building design, as the members could essentially be disassembled, as both glulam and CLT members were originally designed and shipped as individual, prefabricated elements. Reuse, in the original form, may be more difficult with a cast-in-place reinforced concrete structure, due to its systemic design and monolithic construction. Recycling or reprocessing could be applied to both the timber and concrete systems, as EWPs and dimensional lumber could be chipped and reprocessed as other, lower grade wood

products, such as particle board or oriented strand board. Similarly, reinforced concrete can be crushed and used in low-specification applications such as backfill or bedding material for road construction. Crushed concrete can also substitute for natural aggregates in the production of new concrete (Müller, 2002), although it is generally blended with fresh aggregate (Langer, 2009, p. 12). The steel rebar can be recycled in order to make other useful, lower-grade metal products. The option of energy recovery was available only for the heavy timber structure in the form of heat or electricity generation. As was demonstrated graphically in Figure 50, there are several locations along the wood products supply chain that generate biomass waste products, with one being the building demolition phase, that are capable of being used as biofuel to generate energy. The accessibility of potential energy in the heavy timber-framed design was reflected in the feedstock category of the building's embodied energy calculation (refer to Figure 44 and Section 4.1.3). Finally, disposal of demolition products in a landfill was an option for both the concrete- and timber-framed alternatives of Discovery Place. There are ensuing waste management, land use and subsequent environmental impacts associated with land filling that will not be discussed here.

It was difficult to estimate with certainty whether the concrete- or timber-framed design was more environmentally advantageous with respect to end-of-life disposal options. It was evident that the timber-framed design alternative of Discovery Place – Building 12 had additional disposal options, including reuse and biomass energy recovery, which were not as relevant or applicable to the reinforced concrete design scenario.

## **5.0 – CONCLUSIONS**

This impetus for this research project stemmed from a growing demand to understand, measure, and construct building infrastructure that is more sustainable and less environmentally detrimental. The mountain pine beetle epidemic that has plagued the lodgepole pine forests of the Pacific Northwest over the past decade, along with recent legislative changes in the province of British Columbia that now allow for sixstorey timber-framed construction and mandate wood building materials be the first choice in all publicly funded building infrastructure projects were also motivations behind this research. Finally, as building operational energy use declines, the rising importance of understanding and interpreting the embodied energy and environmental impacts associated with other life cycle stages besides the building use phase is becoming more significant, especially when moving from a conventional approach to the high performance building design and construction realm. What are the comparative environmental impacts of a mid-rise, non-residential building, located in British Columbia, which uses a) cast-in-place reinforced concrete exclusively or b) a hybrid laminated timber (CLT and glulam) and concrete frame as the primary structural support system? This was the overarching research question that was addressed in this study. In conjunction, the structural and environmental performance profiles for a new North American timber building product, cross-laminated timber, were developed and incorporated in the comparative LCA framework and results.

A case study building was selected in Burnaby, British Columbia; Discovery Place – Building 12, a reinforced concrete-framed, five-storey office building with three levels of underground parking. Using the plan and elevation layouts of the original concrete building, a redesigned, functionally equivalent hybrid laminated timber-framed alternative was conceived. The heavy timber-framed design utilized glued-laminated timber beams and columns, cross-laminated timber floor and roof plates, with reinforced concrete used for the below-grade foundations, parking level slabs, above- and belowgrade elevator/stair cores and primary shear walls.

After the structural and building enclosure designs were completed and equivalent structural design and envelope heat resistance values were verified, a bill of materials was calculated for both the concrete- and heavy timber-framed design alternatives. This bill

of construction materials was used to evaluate the environmental impact of each design scenario using life cycle assessment. The system boundary of the LCA study was cradle-to-gate, considering a 50-year building lifetime horizon. The environmental burdens associated with each building product were considered from raw materials acquisition, through the manufacture/processing stages, accounting for the production and use of fuels, electricity, and heat, as well as taking into account transportation/distribution impacts at all points along the product supply chain. The boundaries of the study began at the raw materials extraction and finished at the entrance to the construction site gate, with the inclusion of building material and component replacement over the course of the 50-year building life cycle. A combination of publicly available North American databases (BEES<sup>®</sup> 4.0, ATHENA<sup>®</sup> EcoCalculator and the US LCI Database) as well as on-site, factory measurements (CST Innovations, 2009) were used to account for the material, energy, and emissions flows that occurred throughout the raw material acquisition, manufacturing, and transportation phases of each building product's life cycle.

The final LCA of the reinforced concrete- and laminated timber-framed comparison of Discovery Place – Building 12 illustrated that the timber design scenario had a lower environmental impact than the cast-in-place concrete building, in 10 of 11 environmental impact categories. At a minimum, the heavy timber-framed building demonstrated a 14% improvement over its concrete-framed counterpart, while at a maximum; the timber building was estimated to have a contribution to global warming potential that was 71% lower than the concrete design. Fossil fuel depletion was the only impact category where the concrete-framed design displayed a 6% improvement. The total embodied energy for each alternative design scenario was also calculated and categorized, with the heavy timber and reinforced concrete buildings having cumulative embodied energy contents of 116 and 66 terajoules, respectively.

A combination of uncertainty and sensitivity analyses were performed in an attempt to test the reliability and robustness of the study's results and assumptions. These analyses discussed the LCI building material data sets and sources, the environmental modeling details, intricacies, and gaps that existed in the LCA framework, as well as the advantages, disadvantages, and comparative outcome of using process-

based versus economic input-output LCA methodologies. The use of higher fly ash concrete and a 10% variance in the volume of laminated timber were quantitatively modelled and found not to have a large influence the comparative results of the study. Finally, estimates were gauged as to how the inclusion of the construction and end-of-life stages would alter the comparative LCA results.

### 5.1 – Significance

The results of the present study indicate that when considering a mid-rise office building in the Pacific Northwest, it is environmentally advantageous, in all but one impact category, to construct the structural frame and the enclosure system of a mid-rise office buildings similar to Discovery Place – Building 12 using predominantly laminated timber engineered wood products, instead of cast-in-place reinforced concrete construction. Based on the literature review, there exists no studies related to the environmental impacts of mid-rise commercial office buildings, located in Canada or anywhere else in the world, that compares heavy timber laminated EWP (glulam and CLT) and cast-in-place reinforced concrete construction systems. This comparative LCA study addresses that current knowledge gap. The significance of this work also resulted in expanded technical engineering knowledge, related to both the structural design criteria and the environmental performance characteristics of CLT panels manufactured in Canada from MPB-killed timber. The results from this research are applicable to decision makers in both the public and private sectors; whom are now provided with findings that outline the environmental performance of competing structural and building enclosure alternatives. This research has provided industry stakeholders a deeper knowledge base when confronted with decisions that will determine the design and construction choices of new building projects. With respect to the legislative changes that recently took place in the BCBC and the provincial Wood First Act, the present LCA study reinforces the validity of these government mandates, changes, and amendments, while providing an environmental incentive to use more laminated timber EWPs and construction systems in mid-rise office building applications.

### 5.2 – Future Research Recommendations

Additional research is required in order to improve the quality and comprehensiveness of the present study and other subsequent comparative LCA studies related to building construction systems. The accuracy of this study could be improved by using full-scale CLT manufacturing input data, along with refining the structural design calculations to include additional iterations. With respect to sustainability of the built environment, this comparison was based solely on environmental performance; in order to address the full scope of sustainable design and construction practices, an expansion of the LCA framework to include social and economic indicators is necessary. Tools such as social LCA and life cycle costing are techniques that could possibly be employed in order to expand the scope of a building system comparison to include a more complete sustainable design ideology. The use of region specific and site specific environmental modeling refinements would also aid in depicting a clearer picture of the environmental implications that are relevant in the context of an individual region and building site. Predominantly, the data used was industry wide and averaged over the entire North American continent. A Canadian specific LCIA model, such as LUCAS (Tofolletto et al., 2007) would be advantageous in identifying and quantifying parameters and environmental effects that are specific to Canada. Further research is also needed to identify and develop building product LCI data sets for other relevant environmental impact categories, such as soil salinity, erosion, habitat alteration, biodiversity loss and land use impacts. This would aid in providing an even clearer picture of the comparative life cycle impact assessment analysis. Furthermore, additional research related to the onsite construction phase and end-of-life scenarios is required in order to fill the knowledge gaps that exist regarding the impacts associated with these building life cycle stages.

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# **APPENDIX A – Structural Design Calculations**

Derivation of CLT design values:

### **Bending Strength**

# of samples (n) = 3

Specimen Dimensions: width (b) = 1,079 mm; depth (d) = 99 mm; span (L) = 2,154 mm



Figure 51 – Cross Section of 3-ply CLT Panel

Failure loads (P): 205 kN, 233 kN, 249 kN (Chen, 2011, p. 62)

Mean value of failure loads  $(\bar{x}) = 229 \text{ kN}$ 

Standard deviation of failure loads ( $\sigma$ ) = 22.3 kN

Degrees of freedom (n-1) = 2

Moment of inertia (I) = 
$$\left(\frac{bd^3}{12}\right)$$
 = 87,246,052 mm<sup>4</sup>

Coefficient of variation (COV) =  $\left(\frac{\sigma}{x}\right) = 0.097$ 

(ASTM D5457 calculation of COV not employed as sample size was too small, i.e. < 30 specimens) 5<sup>th</sup> percentile failure load ( $P_{5th}$ ) – assume normal distribution  $(\bar{x} - (1.645 \times \sigma)) = 192.4$  kN

k coefficient – 75% confidence interval with two tails (k) = 1.60

5<sup>th</sup> percentile failure load with 75% confidence interval  $(P_{5th,75}) - (ASTM D5456-10a)$ 

$$(P_{5th,75}) = \left(P_{5th} - \left(\frac{k\sigma}{\sqrt{n}}\right)\right) = 171.7 \text{ kN}$$



Figure 52 – Loading Scenario for CLT Bending Test

Bending moment with 
$$\frac{P_{5th,75}}{2}$$
 applied at 0.25*L* & 0.75*L*  

$$(M_{5th,75}) = \left(\frac{P_{5th,75} \times L}{8}\right) = 46.33 \text{ kN} \cdot \text{m}$$

Characteristic value in bending  $(F_b) = \left(\frac{M_{5th,75} \times d}{2I}\right) = 26.3$  MPa

Specified bending strength  $(f_b) = (F_b \times K_r) = 23.1$  MPa

(as per Clause 13.4.3.2 CAN/CSA-086-01)

where

 $K_r$  = reliability normalization factor for bending = 0.88 (as per Table 13.2.3.2 CAN/CSA-O86-01) \*A scaling factor of 0.8, used to convert from test term (short-term) to standard term load duration, has been applied to the  $K_r$  bending factor

#### **Compression Strength**

# of samples (n) = 34

Specimen Dimensions: width (b) = 33 mm; depth (d) = 83 mm; length (L) = 267 mm

Mean value of failure loads ( $\overline{x}$ ) = 37.05 MPa Standard deviation of failure loads ( $\sigma$ ) = 6.15 MPa Degrees of freedom (*n*-1) = 33

Coefficient of variation (COV) =  $\left(\frac{\sigma}{\overline{x}}\right) = 0.166$ 

(ASTM D5457 calculation of COV not employed as sample size was too small, i.e. < 30 specimens) 5<sup>th</sup> percentile failure load ( $P_{5th}$ ) – assume normal distribution  $(\bar{x} - (1.645 \times \sigma)) = 26.9$  MPa k coefficient – 75% confidence interval with two tails (k) = 1.17 5<sup>th</sup> percentile failure load with 75% confidence interval ( $P_{5th,75}$ ) – (ASTM D5456-10a)

$$(P_{5th,75}) = \left(P_{5th} - \left(\frac{k\sigma}{\sqrt{n}}\right)\right) = 25.7 \text{ MPa}$$

Characteristic value in compression parallel to grain (*c*) = 25.7 MPa Specified compression parallel to grain strength ( $f_c$ ) = ( $c \times K_r$ ) = 20.6 MPa

(as per Clause 13.4.3.4 CAN/CSA-086-01)

where

 $K_r$  = reliability normalization factor - compression parallel to grain = 0.80 (as per Table 13.2.3.2 CAN/CSA-O86-01) \*A scaling factor of 0.8, used to convert from test term (short-term) to standard term load duration, has been applied to the  $K_r$  compression parallel to grain factor

References: (Beyer, 1986; Madson, 1992; CAN/CSA-O86-01; Wood Design Manual 2005 Commentary [*pg. 695, Clause 13.2.3 & Clause 13.2.3.6*]; ASTM D5456; ASTM D5457; Lam & Chen, 2008; Chen, 2011)

### Sample structural design calculations:

### CLT Roof Plate

Loading Scenario Ground snow load = 2.6 kPa Rain load = 0.6 kPa SDL = 1.2 kPa S/W (assume 7-ply CLT, d = 231 mm) = (500 kg/m<sup>3</sup>)(0.231 m)(9.81 m/s<sup>2</sup>) = 1.13 kPa Factored load ( $w_f$ ) = 1.25DL + 1.5LL = 1.25(1.2 + 1.13) + 1.5(2.6 + 0.6) = 7.7 kPa Maximum span (L) = 8.382 m

#### Moment Resistance

Factored moment – assuming single span UDL & 1 m width,  $(M_f) = \left(\frac{w_f L^2}{8}\right) = 68 \text{ kN} \cdot \text{m}$ 

Moment resistance  $(M_r)$  – modelled after glulam (Section 6.5.6.5, CAN/CSA-086-01)

 $M_r$  = lesser of  $M_{r1}$  or  $M_{r2}$ 

$$M_{r1} = \emptyset F_b S K_x K_{zbg}$$

 $M_{r2} = \emptyset F_b S K_x K_L$ 

Ø = 0.9

$$F_b = f_b(K_D K_H K_{Sb} K_T) = (23.1 \text{ MPa})(1.0^{\text{a}})(1.1^{\text{b}})(1.0^{\text{c}})(1.0^{\text{d}}) = 25.44 \text{ MPa}$$

a) standard duration load

b) Table 5.4.4, refer to built up beams

- c) dry service condition
- d) no fire retardant treatment

$$S = \left(\frac{bd^2}{6}\right) = 8,893,500 \text{ mm}^3$$

 $K_x = 1.0$  (straight member)  $K_{zbg} = 1.03(BL)^{-0.18} \le 1.0 \rightarrow B = 0.14$   $K_{zbg} = 1.0$  $K_L = 1.0$  when  $C_B < 10$
$$C_B = \sqrt{\frac{1.92 \, l_v d}{b^2}} = 1.93$$
 when  $l_v = 8382$  mm  $\therefore$  K<sub>L</sub> = 1.0

 $M_r = (0.9)(25.4 \text{ MPa})(8,893,500 \text{ mm}^3)(1.0)(1.0) = 203 \text{ kN} \cdot \text{m}$ 

 $M_r > M_f \rightarrow 203 > 68 \text{ kN} \cdot \text{m}$  : 231 deep CLT is acceptable for ultimate bending strength.

#### Shear Resistance

Factored shear force – simply supported UDL & 1 m width,  $(V_f) = \left(\frac{w_f L}{2}\right) = 32.4$  kN

Volume of CLT roof panel =  $(3 \text{ m})(0.231 \text{ m})(8.382 \text{ m}) = 5.8 \text{ m}^3 > 1 \text{ m}^3$ . use Case 2.  $V_r = \emptyset F_v 0.48 A_g K_N C_v Z^{0.18}$  $\emptyset = 0.9$ 

$$F_v = f_v(K_D K_H K_{Sv} K_T) = (1.4 \text{ MPa})(1.0^{\text{a}})(1.1^{\text{b}})(1.0^{\text{c}})(1.0^{\text{d}}) = 1.54 \text{ MPa}$$

- a) standard duration load
- b) Table 5.4.4, refer to built up beams
- c) dry service condition
- d) no fire retardant treatment

$$A_g = (3,000 \text{ mm})(231 \text{ mm}) = 693,000 \text{ mm}^2$$

 $K_N = 1.0$  (no notches)

 $C_v = 3.69$  (Table 6.5.7.4B)

$$Z = 5.8 \text{ m}^3$$

$$V_r = (0.9)(1.54 \text{ MPa})(693,000 \text{ mm}^2)0.48(3.69)(5.8 \text{ m}^3)^{-0.18} = 1,143 \text{ kN}$$

$$W_f = (7.7 \text{ kPa})(3 \text{ m})(8.382 \text{ m}) = 194 \text{ kN}$$

- $V_r > W_f \rightarrow 1,143 > 194 \text{ kN}$
- : 231 deep CLT is acceptable for ultimate shear strength.

#### Serviceability – Deflection Criteria

Total load (DL + LL):

$$\Delta_{\max,TL} = \left(\frac{L}{180}\right) = 47 \text{ mm}$$
$$\Delta_{TL} = \left(\frac{5_{WTL}L^4}{384E_sI}\right) = 32 \text{ mm}$$

 $w_{TL} = 5.53$  N/mm (unfactored total load)  $E_s = 10,050$  MPa (*Chen*, 2009)

Live load (LL only):

$$\Delta_{\text{max,LL}} = \left(\frac{L}{240}\right) = 35 \text{ mm}$$
$$\Delta_{\text{LL}} = \left(\frac{5_{W_{LL}}L^4}{384 E_s I}\right) = 18 \text{ mm}$$

 $w_{LL} = 3.2 \text{ N/mm}$  (unfactored live load)

### Governing Design Criteria

$$\left(\frac{M_r}{M_f}\right) = 3.0, \left(\frac{V_r}{W_f}\right) = 5.9, \left(\frac{\Delta_{\max,TL}}{\Delta_{TL}}\right) = 1.5, \left(\frac{\Delta_{\max,LL}}{\Delta_{LL}}\right) = 1.9$$

: governing design criteria is total load deflection ( $\Delta_{TL}$ ).

# CLT Roof Plate Layout

- based on total load deflection as governing design criteria and a simplysupported span with UDL

$$L_{max} = \left( \sqrt[3]{\frac{384 E_s I}{5 \cdot 180 w_{TL}}} \right)$$

<b>Table 12 –</b>	CLT Roo	f Lavout ba	sed on Total	Load Deflection
		•		

CLT Depth - d (mm)	Maximum Clear Span - $L_{max}(m)$		
99	4.07		
165	6.79		
231	9.51		
297	12.2		

# <u>CLT Floor Plate – Typical Floors (2<sup>nd</sup> – 5<sup>th</sup>)</u>

Loading Scenario

LL = 3.1 kPa SDL = 1.2 kPa S/W (assume 7-ply CLT, d = 231 mm) = (500 kg/m<sup>3</sup>)(0.231 m)(9.81 m/s<sup>2</sup>) = 1.13 kPa Factored load ( $w_f$ ) = 1.25DL + 1.5LL = 1.25(1.2 + 1.13) + 1.5(3.1) = 7.6 kPa Maximum span (L) = 8.382 m

#### Moment Resistance

Factored moment – assuming single span UDL & 1 m width,  $(M_f) = \left(\frac{w_f L^2}{8}\right) = 66 \text{ kN} \cdot \text{m}$ 

Moment resistance  $(M_r)$  – modelled after glulam (Section 6.5.6.5, CAN/CSA-086-01)

 $M_r$  = lesser of  $M_{r1}$  or  $M_{r2}$ 

$$M_{r1} = \emptyset F_b S K_x K_{zbg}$$

$$M_{r2} = \emptyset F_b S K_x K_L$$

$$\emptyset = 0.9$$

$$F_b = f_b (K_D K_H K_{Sb} K_T) = (23.1 \text{ MPa})(1.0^{\text{a}})(1.1^{\text{b}})(1.0^{\text{c}})(1.0^{\text{d}}) = 25.44 \text{ MPa}$$
a) standard duration load  
b) Table 5.4.4, refer to built up beams  
c) dry service condition  
d) no fire retardant treatment

$$S = \left(\frac{bd^2}{6}\right) = 8,893,500 \text{ mm}^3$$

 $K_x = 1.0$  (straight member)

$$K_{zbg} = 1.03(BL)^{-0.18} \le 1.0 \rightarrow B = 0.14$$

 $K_{zbg} = 1.0$ 

 $K_L = 1.0$  when  $C_B < 10$ 

$$C_B = \sqrt{\frac{1.92 l_v d}{b^2}} = 1.93$$
 when  $l_v = 8382$  mm  $\therefore$  K<sub>L</sub> = 1.0

 $M_r = (0.9)(25.4 \text{ MPa})(8,893,500 \text{ mm}^3)(1.0)(1.0) = 203 \text{ kN} \cdot \text{m}$ 

 $M_r > M_f \rightarrow 203 > 66 \text{ kN} \cdot \text{m}$ 

: 231 deep CLT is acceptable for ultimate bending strength.

#### Shear Resistance

Factored shear force – assuming UDL & a 1 m width,  $(V_f) = \left(\frac{w_f L}{2}\right) = 31.7$  kN

Volume of CLT roof panel =  $(3 \text{ m})(0.231 \text{ m})(8.382 \text{ m}) = 5.8 \text{ m}^3 > 1 \text{ m}^3$ . use Case 2.  $V_r = \emptyset F_v 0.48 A_g K_N C_v Z^{0.18}$ Ø = 0.9 $F_{\nu} = f_{\nu}(K_D K_H K_{S\nu} K_T) = (1.4 \text{ MPa})(1.0^{\text{a}})(1.1^{\text{b}})(1.0^{\text{c}})(1.0^{\text{d}}) = 1.54 \text{ MPa}$ a) standard duration load b) Table 5.4.4, refer to built up beams c) dry service condition d) no fire retardant treatment  $A_g = (3,000 \text{ mm})(231 \text{ mm}) = 693,000 \text{ mm}^2$  $K_N = 1.0$  (no notches)  $C_v = 3.69$  (Table 6.5.7.4B)

$$Z = 5.8 \text{ m}^3$$

- $V_r = (0.9)(1.54 \text{ MPa})(693,000 \text{ mm}^2)0.48(3.69)(5.8 \text{ m}^3)^{-0.18} = 1,143 \text{ kN}$
- $W_f = (7.6 \text{ kPa})(3 \text{ m})(8.382 \text{ m}) = 191 \text{ kN}$

 $V_r > W_f \rightarrow 1,143 > 191 \text{ kN}$ 

: 231 deep CLT is acceptable for ultimate shear strength.

#### Serviceability – Deflection Criteria

Total load (DL + LL):

$$\Delta_{\max,\mathrm{TL}} = \left(\frac{L}{180}\right) = 47 \mathrm{~mm}$$

$$\Delta_{\rm TL} = \left(\frac{5_{WTL}L^4}{384 E_s I}\right) = 31 \text{ mm}$$

 $w_{TL} = 5.43$  N/mm (unfactored total load)

 $E_s = 10,050$  MPa (*Chen*, 2009)

Live load (LL only):

$$\Delta_{\text{max,LL}} = \left(\frac{L}{360}\right) = 23 \text{ mm}$$
$$\Delta_{\text{LL}} = \left(\frac{5_{WLL}L^4}{384_{E_s}I}\right) = 18 \text{ mm}$$

 $w_{LL} = 3.1$  N/mm (unfactored live load)

# Governing Design Criteria

$$\left(\frac{M_r}{M_f}\right) = 3.1, \left(\frac{V_r}{W_f}\right) = 6.0, \left(\frac{\Delta_{\max,TL}}{\Delta_{TL}}\right) = 1.5, \left(\frac{\Delta_{\max,LL}}{\Delta_{LL}}\right) = 1.3$$

: governing design criteria is live load deflection ( $\Delta_{LL}$ ).

# Typical CLT Floor Plate Layout

- based on live load deflection as governing design criteria and a simplysupported span with UDL

$$L_{max} = \left( \sqrt[3]{\frac{384 E_s I}{5 \cdot 360 w_{LL}}} \right)$$

Table 13 – CLT Floor Layout based on Live Load Deflection

CLT Depth - d (mm)	Maximum Clear Span - $L_{max}(m)$
99	3.92
165	6.54
231	9.15
297	11.7

# <u>Glulam Beam – Typical Floors (2<sup>nd</sup> – 5<sup>th</sup>)</u>

Loading Scenario LL = 3.1 kPa SDL = 1.2 kPa DL = S/W + DL<sub>CLT</sub> = 1.6 kN/m + 1.13 kPa Maximum span (*L*) = 9.45 m Tributary width = 8.382 m Tributary area (*A<sub>T</sub>*) = 79.2 m<sup>2</sup> Factored load (*w<sub>f</sub>*) = 1.25DL + 1.5(0.66 · LL) = 52 kN/m Maximum beam depth = 886 mm (due to drop ceiling height) Live load reduction factor (LLRF) =  $0.3 + \left(\sqrt{\frac{9.8}{A_T}}\right) = 0.65$ Factored moment – assuming UDL, (*M<sub>f</sub>*) =  $\left(\frac{w_f L^2}{8}\right) = 580$  kN·m Factored shear force – assuming UDL, (*V<sub>f</sub>*) =  $\left(\frac{w_f L}{2}\right) = 246$  kN

### Serviceability – Deflection Criteria

For total load (DL + LL):

$$\Delta_{\max,TL} = \left(\frac{L}{180}\right)$$
$$E_{s}I_{req'd} = 180\left(\frac{5w_{TL}L^{3}}{384}\right) = 75,137 \times 10^{9} \,\mathrm{N} \cdot \mathrm{mm}^{2}$$

 $w_{TL} = 38$  N/mm (unfactored total load)  $E_s = 10,300$  MPa

For total live load (LL only):

$$\Delta_{\rm max,LL} = \left(\frac{L}{360}\right)$$

$$E_s I_{req'd} = 360 \left( \frac{5_{WLL} L^3}{384} \right) = 67,228 \text{ x } 10^9 \text{ N} \cdot \text{mm}^2$$

 $w_{LL} = (3.1 \text{ kPa})(8.382 \text{ m})(0.65) = 17 \text{ N/mm}$  (unfactored live load with LLRF)

Try 315 x 760, S-P 20f-E

 $E_s I_{provided} = 118,688 \text{ x } 10^9 \text{ N} \cdot \text{mm}^2 > E_s I_{reg'd}$ 

Moment Resistance

Moment resistance  $(M_r)$  – modelled after glulam (*Section 6.5.6.5, CAN/CSA-086-01*)

 $M_r = M_r$ '(lesser of  $K_L$  or  $K_{zbg}$ )

 $M_r$ ' = 699 kN $\cdot$ m

 $K_{zbg} = 0.843$  (as per Table 2.11, pg. 59)

 $K_L = 1.0$  when  $C_B < 10$ 

CB = 
$$\sqrt{\frac{1.92 l_v d}{b^2}}$$
 = 11.8 when  $l_v$  = 9,449 mm  $\therefore$  K<sub>L</sub> = 0.94

 $M_r = (699 \text{ kN} \cdot \text{m})(0.846) = 591 \text{ kN} \cdot \text{m}$ 

 $M_r > M_f \rightarrow 591 > 580 \text{ kN} \cdot \text{m}$ 

: 315 x 760, S-P 20f-E is acceptable for ultimate bending strength.

### Shear Resistance

Volume of glulam beam =  $(0.315 \text{ m})(0.76 \text{ m})(9.449 \text{ m}) = 2.3 \text{ m}^3 > 1 \text{ m}^3$   $\therefore$  use Case 2.  $V_r = \emptyset F_v 0.48 A_g K_N C_v Z^{0.18}$   $F_v = f_v (K_D K_H K_{Sv} K_T) = (1.75 \text{ MPa})(1.0^{\text{a}})(1.0^{\text{b}})(1.0^{\text{c}})(1.0^{\text{d}}) = 1.75 \text{ MPa}$ a) standard duration load

- b) Table 5.4.4, refer to built up beams
- c) dry service condition
- d) no fire retardant treatment

$$A_g = (315 \text{ mm})(760 \text{ mm}) = 239,400 \text{ mm}^2$$
  
 $K_N = 1.0 \text{ (no notches)}$   
 $C_v = 3.69 \text{ (Table 6.5.7.4B of CAN/CSA 086-01)}$   
 $Z = 2.3 \text{ m}^3$   
 $V_r = (0.9)(1.75 \text{ MPa})(239,400 \text{ mm}^2)0.48(3.69)(2.3 \text{ m}^3)^{-0.18} = 575 \text{ kN}$ 

 $W_f = (52 \text{ kN/m})(9.45 \text{ m}) = 491 \text{ kN}$ 

- $V_r > W_f \rightarrow 575 > 491 \text{ kN}$
- : 315 x 760, S-P 20f-E is acceptable for ultimate shear strength.

Bearing/Crushing Resistance (compression perpendicular to grain)

Factored bearing force  $(Q_f) = 31.7$  kN per metre length (from typical CLT floor plate) Bearing width = (0.5)(315 mm) = 158 mmBearing length = 1,000 mm Bearing area  $(A_b) = 157,500 \text{ mm}^2$ Factored bearing resistance  $(Q_r) = \emptyset F_{cp} A_b K_B K_{zcp}$  $F_{cp} = f_{cp} (K_D K_{Scp} K_T) = (5.8 \text{ MPa})(1.0^{\text{a}})(1.1^{\text{b}})(1.0^{\text{c}}) = 1.54 \text{ MPa}$ 

- a) standard duration load
- b) dry service condition
- c) no fire retardant treatment

 $A_b = (158 \text{ mm})(1,000 \text{ mm}) = 157,500 \text{ mm}^2$ 

$$Q_r = (0.8)(5.8 \text{ MPa})(157,500 \text{ mm}^2) = 731 \text{ kN}$$

 $Q_r > Q_f \rightarrow 731 > 32 \text{ kN}$ 

: 315 x 760, S-P 20f-E is acceptable for ultimate bearing strength.

#### Glulam Beam - Roof

Loading Scenario LL = snow + rain = 3.2 kPa SDL = 1.2 kPa DL = S/W + DL<sub>CLT</sub> + SDL = 1.6 kN/m + 1.13 kPa + 1.2 kPa Maximum span (L) = 9.45 m Tributary width = 8.382 m Tributary area ( $A_T$ ) = 79.2 m<sup>2</sup> Factored load ( $w_f$ ) = 1.25DL + 1.5LL = 67 kN/m Maximum beam depth = 886 mm (due to drop ceiling height) Select 365 x 836, S-P 20f-E – design calculation methodology similar to **Glulam Beam** – **Typical Floors (2-5)**, above.

### Ponding Check

$$\frac{\sum \Delta}{w} < 65 \quad (Clause \ 4.5.4, \ CAN/CSA-O86-O1)$$

 $\sum \Delta =$  sum of deflections due to this load, mm, of all the components of the system

(decking, secondary beams, primary beams, etc.)

w = specified total uniformly distributed load, kN/m<sup>2</sup>

$$\Delta_{\rm CLT} = \left(\frac{5_{W_{LL}}L^4}{384 E_s I}\right) = 3.8 \text{ mm}$$

L = 8382 mm

$$E_s = 10,050 \text{ MPa} (Chen, 2009)$$

 $I = 1.027 \text{ x } 10^6 \text{ mm}^4$ 

 $w_{LL}$  = 3.2 N/mm (unfactored live load per metre width)

$$\Delta_{\text{Glulam}} = \left(\frac{5_{WLL}L^4}{384E_sI}\right) = 15.2 \text{ mm}$$

L = 9450 mm

 $E_s = 10,300 \text{ MPa} (Table 6.3, CAN/CSA-O86-01)$  $I = 17,771 \times 10^6 \text{ mm}^4$ 

$$w_{LL} = = \frac{(3.2 \times 79.2)}{9.450} = 26.8 \text{ N/mm} \text{ (unfactored live load)}$$

$$\frac{\sum \Delta}{w} = \frac{(3.8 + 15.2)}{3.2} = 6 < 65$$
 (Acceptable)

# <u>Glulam Beam – Spandrel Edge Beam Typical Floors (2<sup>nd</sup> – 5<sup>th</sup>)</u>

Loading Scenario LL = 3.1 kPa SDL = 1.2 kPa DL = S/W + DL<sub>CLT</sub> + DL<sub>curtain wall</sub> + SDL = 1.6 kN/m + 1.13 kPa + 1 kPa + 1.2 kPa Maximum span (L) = 10.67 m Tributary width = 4.191 m Tributary height = 3.886 m (height of curtain wall supported by edge beam) Factored load ( $w_f$ ) = 1.25DL + 1.5LL = 39 kN/m Maximum beam depth = 886 mm (due to drop ceiling height)

Select 265 x 798, S-P 20f-E – design calculation methodology similar to **Glulam Beam** – **Typical Floors (2-5)**, above.

#### **CLT Exterior Wall**

<u>Loading Scenario</u> Unsupported height  $(L_u) = 3.962$  m

Tributary width = 5.334 m

- consider only 1 m length of wall

Floor	Factored Load (kN)	
Roof	42	
5 <sup>th</sup>	83	
$4^{\text{th}}$	124	
3 <sup>rd</sup>	165	
$2^{nd}$	206	

 Table 14 – CLT Wall Loading by Floor (2<sup>nd</sup> to Roof)

Factored axial load  $(P_f) = 206 \text{ kN}$ 

- Try 5-ply CLT panel, 
$$b = 1,000 \text{ mm}, d = 165 \text{ mm}$$

Factored axial resistance  $(P_r) = \emptyset F_c A_{net} K_{zcg} K_c$ 

$$Ø = 0.8$$

$$F_c = f_c(K_D K_H K_{Sc} K_T)$$
 (20.6 MPa)(1.0)(1.0)(0.75)(1.0) = 15.5 MPa

 $f_c = 20.6 \text{ MPa}$ 

a) standard duration load

b) wet service condition

c) no fire retardant treatment

 $A_{net} = (3 \text{ x } 33 \text{ mm})(1000 \text{ mm}) = 99,000 \text{ mm}^2$ 

(consider only cross-sectional area of CLT where load is parallel to grain)

$$K_{zcg} = 0.68(bdL_u)^{-0.13} \le 1.0$$
  

$$K_{zcg} = 0.719$$
  

$$K_c = \left(1 + \frac{f_c K_{zcg} \left(\frac{L_u}{d}\right)^3}{35(0.87) E_c}\right)^{-1} = 0.590$$

$$E_c = 9,700 \text{ MPa}$$
  
 $P_r = (0.8)(15.5 \text{ MPa})(99,000 \text{ mm}^2)(0.719)(0.590) = 519 \text{ kN}$   
 $P_r > P_f \rightarrow 519 > 206 \text{ kN}$ 

: 5-ply, 165 wide CLT is acceptable for ultimate compressive strength.

### **CLT Exterior Columns**

Loading Scenario

Unsupported height ( $L_u$ ) = 7.772 m (double-storey height between  $G - 3^{rd}$ )

Tributary width = 5.334 m

Tributary length = 6.096 m

Tributary area =  $32.5 \text{ m}^2$ 

Floor-to-floor height = 3.81 m

Roof Loading

 $DL = S/W + SDL + DL_{CLT} + DL_{glulam} + DL_{curtain wall} = 106 \text{ kN}$  $LL = \text{snow} + \text{rain} = (3.2 \text{ kPa})(32.5 \text{ m}^2) = 104 \text{ kN}$  $P_f = 1.25(106 \text{ kN}) + 1.5(104 \text{ kN}) = 288 \text{ kN}$ 

 $\frac{\text{Typical Floor Loading } (2^{\text{nd}} - 5^{\text{th}})}{\text{DL} = \text{S/W} + \text{SDL} + \text{DL}_{\text{CLT}} + \text{DL}_{\text{glulam}} + \text{DL}_{\text{curtain wall}} = 116 \text{ kN}}$  $\text{LL} = (3.1 \text{ kPa})(32.5 \text{ m}^2) = 102 \text{ kN}$  $P_f = 1.25(106 \text{ kN}) + 1.5(102 \text{ kN}) = 297 \text{ kN}$ 

Table 15 – Exterior CLT Column Loading by Floor (Ground to Roof)

Floor	Factored Load (kN)
Roof	288
5 <sup>th</sup>	585
$4^{\text{th}}$	882
$3^{\rm rd}$	1,179
$2^{nd}$	-
G	1,218

Factored axial load  $(P_f) = 1,218 \text{ kN}$ 

- Try 9-ply CLT panel, b = 2,000 mm, d = 297 mm

Factored axial resistance  $(P_r) = \emptyset F_c A_{net} K_{zcg} K_c$ 

Ø = 0.8

$$F_c = f_c(K_D K_H K_{Sc} K_T)$$
 (20.6 MPa)(1.0)(1.0)(0.75)(1.0) = 15.5 MPa

 $f_c = 20.6 \text{ MPa}$ 

- a) standard duration load
- b) wet service condition
- c) no fire retardant treatment

 $A_{net} = (5 \text{ x } 33 \text{ mm})(2,000 \text{ mm}) = 330,000 \text{ mm}^2$ 

(consider only cross-sectional area of CLT where load is parallel to grain)  $K_{zcg} = 0.68(bdL_u)^{-0.13} \le 1.0$ 

$$K_{zcg} = 0.557$$

$$K_c = \left(1 + \frac{f_c K_{zcg} \left(\frac{L_u}{d}\right)^3}{35(0.87) E_c}\right)^{-1} = 0.590$$

$$E_c = 9,700 \text{ MPa}$$
  
 $P_r = (0.8)(15.5 \text{ MPa})(330,000 \text{ mm}^2)(0.557)(0.590) = 1,340 \text{ kN}$   
 $P_r > P_f \rightarrow 1,340 > 1,216 \text{ kN}$   
 $\therefore 9$ -ply, 297 wide CLT is acceptable for ultimate compressive strength.

### **Glulam Columns – Typical Floors**

<u>Loading Scenario</u> Unsupported height ( $L_u$ ) = 3.81 m Tributary area = 72.6 m<sup>2</sup>

Live load reduction factor (LLRF) =  $0.3 + \left(\sqrt{\frac{9.8}{A_T}}\right) = 0.667$ 

 $\frac{\text{Roof Loading}}{\text{DL} = \text{SDL} + \text{DL}_{\text{CLT}} + \text{DL}_{\text{glulam}} = 194 \text{ kN}$  $\text{LL} = \text{snow} + \text{rain} = (3.2 \text{ kPa})(72.6 \text{ m}^2) = 232 \text{ kN}$ 

 $P_f = 1.25(106 \text{ kN}) + 1.5(104 \text{ kN}) = 593 \text{ kN}$ 

 $\frac{\text{Typical Floor Loading } (2^{\text{nd}} - 5^{\text{th}})}{\text{DL} = \text{SDL} + \text{DL}_{\text{CLT}} + \text{DL}_{\text{glulam BM}} + \text{DL}_{\text{glulam COL}} = 195 \text{ kN}}$  $\text{LL} = (3.1 \text{ kPa})(72.6 \text{ m}^2)(0.667) = 150 \text{ kN}$  $P_f = 1.25(195 \text{ kN}) + 1.5(150 \text{ kN}) = 469 \text{ kN}$ 

Floor	Factored Load (kN)	
5 <sup>th</sup> – U/S of Roof	593	
$4^{th} - U/S \text{ of } 5^{th}$	1,062	
$3^{rd}$ – U/S of $4^{th}$	1,531	
$2^{nd} - U/S \text{ of } 3^{rd}$	2,000	
$G - U/S$ of $2^{nd}$	2,469	

Table 16 – Glulam Column Loading (Ground to 5<sup>th</sup>)

Factored axial resistance  $(P_r) = \emptyset F_c A_{net} K_{zcg} K_c$ 

Ø = 0.8

# $F_c = f_c(K_D K_H K_{Sc} K_T)$ (25.2 MPa)(1.0)(1.0)(1.0)(1.0) = 25.2 MPa

- $f_c = 25.2 \text{ MPa} (\text{S-P } 12\text{c-E})$
- a) standard duration load
- b) dry service condition
- c) no fire retardant treatment

$$K_{zcg} = 0.68(bdL_u)^{-0.13} \le 1.0$$
  

$$K_{zcg} = 0.557$$
  

$$K_c = \left(1 + \frac{f_c K_{zcg} \left(\frac{L_u}{d}\right)^3}{35(0.87) E_c}\right)^{-1} = 0.544$$

 $E_c = 9,700 \text{ MPa}$ 

Table 17 – Minimum Glulam Column Sizes (Ground to 5<sup>th</sup>)

Floor	Size (mm x mm)		
5 <sup>th</sup> to U/S of Roof	215 x 228 (S-Р 12с-Е)		
$4^{\text{th}}$ to U/S of $5^{\text{th}}$	265 x 342 (S-P 12c-E)		
$3^{rd}$ to U/S of $4^{th}$	315 x 380 (S-P 12с-E)		
$2^{nd}$ to U/S of $3^{rd}$	365 x 418 (S-P 12c-E)		
G to U/S of 2 <sup>nd</sup>	365 x 418 (D.Fir-L 16c-E)		

- Column sizes selected based on design procedure outlined above

# Lateral Analysis – Wind Loading:

### Wind Loading – Ultimate Limit State (concrete & timber designs)

		North – South	East – West
		$p_{max} = 0.934 \ kPa$	$p_{max} = 0.832 \ kPa$
Floor Level	<b>h</b> <sub>i</sub> ( <b>m</b> )	$\mathbf{F}_{\mathbf{x}}(\mathbf{kN})$	$\mathbf{F}_{\mathbf{x}}(\mathbf{kN})$
Roof	19.2	151	150
5 <sup>th</sup>	15.4	193	220
$4^{\text{th}}$	11.6	182	208
3 <sup>rd</sup>	7.77	168	192
$2^{nd}$	3.96	162	185

#### Table 18 – Wind Loading

- Force from wind on elevator machine room and stair covering added to roof level

- Wind analysis calculations as per NBCC 2005

# Lateral Analysis – Earthquake Loading:

#### **Dead Load Calculation** (*reinforced concrete structure*)

Floor Level	SDL (kPa)	S/W (kN)	Floor Area (ft <sup>2</sup> )	Total Floor Weight - W <sub>i</sub> (kN)
Roof	2.0 (incl. 25% rain + snow)	19,089	28,129	24,307
5 <sup>th</sup>	1.2	24,627	32,234	28,212
4 <sup>th</sup>	1.2	23,314	32,234	26,898
3 <sup>rd</sup>	1.2	23,460	32,234	27,045
$2^{nd}$	1.2	21,186	29,047	24,416

 Table 19 – Floor Weights (Concrete Design)

- Reinforced concrete density taken as 2,400 kg/m<sup>3</sup>

### Earthquake Loading (reinforced concrete structure)

				North – South	East – West
				v = 0.096W	v = 0.0804W
Floor Level	<b>h</b> <sub>i</sub> ( <b>m</b> )	W <sub>i</sub> (kN)	$h_i W_i (kN \cdot m)$	$\mathbf{F}_{\mathbf{x}}\left(\mathbf{kN}\right)$	$\mathbf{F}_{\mathbf{x}}\left(\mathbf{kN}\right)$
Roof	19.2	24,307	466,749	3,859	3,232
5 <sup>th</sup>	15.4	28,212	434,243	3,591	3,007
4 <sup>th</sup>	11.6	26,898	311,545	2,576	2,157
3 <sup>rd</sup>	7.77	27,045	210,203	1,738	1,456
$2^{nd}$	3.96	24,416	96,747	800	670
Total		130,878	1,519,486		
Base Shear				12,564	10,523

Table 20 – Earthquake Loading (Concrete Design)

- Force from wind on elevator machine room and stair covering added to roof level
- Earthquake analysis calculations as per BCBC 1998
- Torsional effects have been neglected

### Dead Load Calculation (laminated timber structure)

Floor Level	SDL (kPa)	S/W (kN)	Floor Area (ft <sup>2</sup> )	Total Floor Weight - W <sub>i</sub> (kN)
Roof	2.0 (incl. 25% rain + snow)	5,837	28,129	11,054
5 <sup>th</sup>	1.2	7,421	32,234	11,006
4 <sup>th</sup>	1.2	7,574	32,234	11,158
3 <sup>rd</sup>	1.2	7,603	32,234	11,188
$2^{nd}$	1.2	7,299	29,047	10,529

Table 21 – Floor Weights (Timber Design)

- Laminated timber (CLT & glulam) density taken as 500 kg/m<sup>3</sup>
- Reinforced concrete (elevator & stair cores + SW3 shear wall) density taken as 2,400 kg/m<sup>3</sup>
- Self-weight (S/W) includes concrete elevator & stairs cores + SW3 primary shear wall

# Earthquake Loading (laminated timber structure)

				North – South	East – West
				v = 0.112W	v = 0.0938W
Floor Level	<b>h</b> <sub>i</sub> ( <b>m</b> )	W <sub>i</sub> (kN)	$h_i W_i (kN \cdot m)$	$\mathbf{F}_{\mathbf{x}}\left(\mathbf{kN}\right)$	$\mathbf{F}_{\mathbf{x}}\left(\mathbf{kN}\right)$
Roof	19.2	11,054	212,266	2,042	1,710
5 <sup>th</sup>	15.4	11,006	169,409	1,630	1,365
4 <sup>th</sup>	11.6	11,158	129,238	1,243	1,041
3 <sup>rd</sup>	7.77	11,188	86,954	836	701
$2^{nd}$	3.96	10,529	41,720	401	336
Total		54,935	639,587		
Base Shear				6,153	5,153

 Table 22 – Earthquake Loading (Timber Design)

- Force from wind on elevator machine room and stair covering added to roof level

- Earthquake analysis calculations as per BCBC 1998

- Torsional effects have been neglected

# **APPENDIX B – Building Envelope Design**

# **Building Envelope – Heat Resistance Values**

### Exterior Wall (E1) Design – Concrete Case

Γ				<b>T</b> T <b>T</b> T <b>I</b>	De	
Material	Conductivity	Thickness	RSI-Value	U-Value	Reference	
Wateria	(W/m/K)	(m)	$(m^2K/W)$	$(W/m^2K)$	Source	
Outdoor air	N/A	N/A	0.029 - 0.043	23.3 - 34.5	(1)	
203 mm concrete wall	0.76 - 2.1	0.203	0.097 - 0.267	3.75 - 10.3	(2) & (3)	
13 mm airspace	N/A	0.013	0.169	5.92	(1) & (4)	
92 mm steel studs @ 400 O/C	45.3	0.092	0.002	500	(2) & (3)	
64 mm R-12 ccSPE insulation	6.2 – 6.87 per	0.064	273 - 302	0.331 -	(5) & (6)	
	inch	0.004	2.73 - 3.02	0.366		
13 mm gypsum board	0.16 - 0.48	0.013	0.026 - 0.080	12.5 - 38.5	(2) & (3)	
Inside air film	N/A	N/A	0.120	8.33	(1)	
Flow through stud – Low		0.321	0.44	2.26	(23% steel	
Flow through stud – High		0.321	0.68	1.47	stud)	
Flow through ccSPF – Low		0.321	3.00	0.333	(77%	
Flow through ccSPF – High		0.321	3.53	0.283	ccPSF)	
				•		
Total – Low		0.321	1.30	0.769	Calas	
Total – High		0.321	1.81	0.552	Calcs. as	
Total – Average		0.321	1.56	0.660	per (3)	

#### Table 23 – Exterior Wall Design (Concrete Structure)

Note:

# Exterior Wall (E1) Design – CLT Case

Material	Conductivity (W/m/K)	Thickness (m)	<b>RSI-Value</b> (m <sup>2</sup> K/W)	U-Value (W/m <sup>2</sup> K)	Reference Source
Outdoor air	N/A	N/A	0.029 - 0.043	23.3 - 34.5	(1)
13 mm cedar siding	0.11	0.013	0.119	8.41	(7)
Vapour permeable membrane	-	0.006	—	-	(3)
165 mm CLT wall	0.12 - 0.15	0.165	1.1 – 1.375	0.727 – 0.909	(2), (3) & (8)
13 mm gypsum board	0.16 - 0.48	0.013	0.026 - 0.080	12.5 - 38.5	(2) & (3)
Inside air film	N/A	N/A	0.120	8.33	(1)
Total – Low		0.196	1.37	0.731	Calaa aa
Total – High		0.196	1.66	0.604	Calcs. as
Total – Average		0.196	1.51	0.667	per (3)

### Table 24 – Exterior Wall Design (CLT Structure)

Note:

# Curtain Wall (E3) Design – Concrete Case

Material	Conductivity	Thickness	<b>RSI-Value</b>	U-Value	Reference
	(W/m/K)	(m)	$(m^2K/W)$	$(W/m^2K)$	Source
Outdoor air	N/A	N/A			
6 mm pane/spandrel glass	unspecified	0.006			
Argon-filled cavity	unspecified	unknown	1 10	0.007	(0)
6 mm interior pane	unspecified	0.006	1.10	0.907	(9)
Mullion	unspecified	unknown			
Inside air film	N/A	N/A			
Spandrel Panel		•		•	
67 mm air space	N/A	0.067	0.119	8.42	(3)
25 mm R-12 semi- rigid insulation	0.04	0.025	0.704	1.42	(3)
92 mm steel studs @ 610 O/C	45.3	0.092	0.002	500	(2) & (3)
13 mm gypsum board	0.16 - 0.48	0.013	0.026 - 0.080	12.5 - 38.5	(2) & (3)
		•		•	•
Flow through stud – Low		~0.197	0.73	1.37	(15%
Flow through stud – High		~0.197	0.79	1.27	steel stud)
Flow through R-12 – Low		~0.197	0.97	1.03	(85%
Flow through R-12 – High		~0.197	1.02	0.98	insulation)
Spandrel panel total – Low		~0.197	0.92	1.08	Calcs. as
Spandrel panel total – High		~0.197	0.98	1.02	per (3)
		•			
Total – Low		~0.197	1.38	0.726	(70%:30%
Total – High		~0.197	1.39	0.718	– vision to
Total – Average		~0.197	1.39	0.722	spandrel)

### Table 25 – Curtain Wall Design (Concrete Case)

Note:

# Curtain Wall (E3) Design – Timber Case

Material	Conductivity	Thickness	<b>RSI-Value</b>	U-Value	Reference
	(W/m/K)	(m)	$(m^2K/W)$	$(W/m^2K)$	Source
Outdoor air	N/A	N/A			
6 mm pane/spandrel glass	unspecified	0.006			
Argon-filled cavity	unspecified	unknown	1 10	0.007	(0)
6 mm interior pane	unspecified	0.006	1.10	0.907	(9)
Mullion	unspecified	unknown			
Inside air film	N/A	N/A			
Spandrel Panel					
92 mm air space	N/A	0.092	0.164	6.10	(3)
19 mm R-12 semi- rigid insulation	0.04	0.019	0.528	1.89	(3)
89 mm wood stud @ 610 O/C	0.12 - 0.15	0.089	0.593 - 0.741	1.35 – 1.69	(2) & (3)
13 mm gypsum board	0.16 - 0.48	0.013	0.026 - 0.080	12.5 - 38.5	(2) & (3)
		•	•	•	
Flow through stud – Low		~0.213	1.31	0.76	(15%
Flow through stud – High		~0.213	1.51	0.56	stud)
Flow through air space – Low		~0.213	0.88	1.13	(85% air
Flow through airspace – High		~0.213	0.94	1.07	space)
Spandrel panel total – Low		~0.213	0.93	1.08	Calcs. as
Spandrel panel total – High		~0.213	0.99	1.01	per (3)
		•	·		
Total – Low		~0.213	1.38	0.726	(70%:30%
Total – High		~0.213	1.40	0.716	– vision to
Total – Average		~0.213	1.39	0.721	spandrel)

### Table 26 – Curtain Wall Design (Timber Case)

Note:

# <u>Roof Design – Timber Case</u>

Material	Conductivity	Thickness	RSI-Value	U-Value	Reference
	(W/m/K)	(m)	$(m^2K/W)$	$(W/m^2K)$	Source
	1	r	ſ	T	
Outdoor air	N/A	N/A	0.029 - 0.043	23.3 - 34.5	(1)
2-ply SBS membrane	_	0.006	0.042	23.7	(10)
32 mm R-12 rigid insulation	0.04	0.032	0.88	1.14	(3)
Vapour barrier	—	0.006	—	—	(3)
99 mm deep CLT	0.12 - 0.15	0.099	0.66 - 0.825	1.21 - 1.52	(2), (3) & (8)
165 mm deep CLT	0.12 - 0.15	0.165	1.10 - 1.375	0.727 – 0.909	(2), (3) & (8)
231 mm deep CLT	0.12 - 0.15	0.231	1.54 – 1.925	0.519 – 0.649	(2), (3) & (8)
297 mm deep CLT	0.12 - 0.15	0.297	1.98 - 2.475	0.404 - 0.505	(2), (3) & (8)
Inside air film	N/A	N/A	0.120	8.33	(1)
Through 99 mm CLT – Low		0.187	1.73	0.577	(7.3% of
Through 99 mm CLT – High		0.187	1.91	0.523	roof area)
Through 165 mm CLT – Low		0.253	2.17	0.460	(10.6% of
Through 165 mm CLT – High		0.253	2.46	0.406	roof area)
Through 231 mm CLT – Low		0.319	2.61	0.383	(67.5% of
Through 231 mm CLT – High		0.319	3.01	0.332	roof area)
Through 297 mm CLT – Low		0.385	3.05	0.328	(14.6% of
Through 297 mm CLT – High		0.385	3.56	0.281	roof area)
Total – Low		0.187	2.52	0.397	Calas
Total – High		0.385	2.89	0.347	Calcs. as
Total – Average		0.312	2.70	0.372	per (3)

### Table 27 – Roof Design (CLT Structure)

Note:

### **Roof Design – Concrete Case**

Material	Conductivity (W/m/K)	Thickness (m)	<b>RSI-Value</b> (m <sup>2</sup> K/W)	U-Value (W/m <sup>2</sup> K)	Reference Source
	· · · ·	• • • •	• · ·	• • •	
Outdoor air	N/A	N/A	0.029 - 0.043	23.3 - 34.5	(1)
2-ply SBS membrane	_	0.006	0.042	23.7	(10)
76 mm R-12 rigid insulation	0.04	0.08	2.11	0.473	(3)
Vapour barrier	—	0.006	—	_	(3)
229 mm concrete slab	0.76 - 2.1	0.23	0.109 - 0.301	3.32 - 9.19	(2) & (3)
64 mm ccSPF insulation	6.2 – 6.87 per inch	0.064	2.73 - 3.02	0.331 – 0.366	(5) & (6)
Inside air film	N/A	N/A	0.120	8.33	(1)
Flow through slab – Low		0.381	2.41	0.414	(ccSPF
Flow through slab – High		0.381	2.62	0.382	applied to
Through $slab + ccSPF - Low$		0.381	5.14	0.194	only 11%
Through slab + ccSPF - High		0.381	5.64	0.177	of roof)
Total – Low		0.381	2.57	0.390	Calaa
Total – High		0.381	2.79	0.359	Calcs. as
Total – Average		0.381	2.68	0.374	per (3)

#### Table 28 – Roof Design (Concrete Structure)

#### **Reference Sources (Tables 23 – 28)**

- (1) ASHRAE Handbook 1981 Fundamentals (Table 1, p. 23.12)
- (2) Harvey (2006)
- (3) Hutcheon & Handegord (1995)
- $(4) \ -www.coloradoenergy.org/procorner/stuff/r-values.htm$
- (5) Honeywell (2009)
- (6) Harvey (2007)
- $(7) www.cedar-siding.org/cedar_products/specifying-siding/physical-properties.htm$
- (8) EU CLT Manufacturers (KLH, Binderholz, Finnforest Merk & Mayr-Melnhof)
- (9) ATHENA<sup>®</sup> (2009)
- (10) www.roofhelp.com/Rvalue.htm

# **APPENDIX C – LCI/LCIA Data Sets and Summaries**

# CLT Manufacturing (pilot-plant scale) – Process Energy Use

Production Stage	Electricity (kJ)	Propane (L)	Remarks			
Planing	18,501	_	30, 30, 10 & 7.5 HP motors @ 60 ft/min.			
Chopping	2,238	_	10 HP @ 5 mins.			
Glue Application	242	_	1 HP @ 4.8 mins.			
Hydraulic Pressing	3,870	_	3 HP @ 2 mins. & 4 kW @ 15 mins.			
Air Compressor	20.411		15 HP @ 2.67 hours			
All Complessor	20,411	—	(Idling @ 10% of full power for 90% of time)			
Miscellaneous						
Forklift	-	2.42	1 tank per week @ 36.3 L/tank			
Dust Collection	6,714	—	15 HP @ 10 mins.			
TOTAL	51,975	2.42				
Waste						
Hog Fuel (sawdust)	-	—	~0.5 kg wood waste			

#### Table 29 – CLT Manufacturing Energy Use

Notes:

(1) - Finger jointing, CNC machining and power tool trimming were not included

(2) -1 HP = 746 J/s

- (3)  $-\min(s) = \min(s)$
- (4) Energy consumption based on the fabrication of a single panel (4'x 12' x 4" deep =  $16 \text{ ft}^3$ )
- (5) Pilot plant capacity was 3 panels per day
- (6) Cold applied PU glue was modelled for production (i.e. no heat required during pressing);
   \*press time & energy use not anticipated to be significantly altered when utilizing PRF glue\*

# LCI Data Set - PRF and Hardener Adhesive

	PRF	Hardener		PRF	Hardener
Resources	lb/lb	1b/1b	Emissions to sir	Ib/Ib	lb/lb
lir	1.54E-01	3.40E-01	Aldehydes	2.00E-05	0.00E+00
litrogen	8.99E-03	0.00E+00	Aromatics	2.00E-05	1.00E-05
Barreite	4.70E-04	4.50E-04	Benzene	0.00E+00	1.00E-05
Sentonite	7.01E-05	0.00E+00	00	4.78E-03	9.21E-04
opper ore	1.10E-03	7.21E-04	CO1	2.23E+00	1.75E+00
FOE OCE	3.00E-04	2.00E-04	Dust	2.14E-03	8.31E-04
imestone	1.20E-03	1.81E-03	Ethene	2.00E-05	2.80E-04
laCl	2.11E-01	2.81E-02	HCOOH	0.00E+00	6.00E-05
litrogen	0.00E+00	5.24E-03	HCL	7.01E-05	0.00E+00
hosphate	7.01E-05	1.20E-04	Hydrocarbons	8.48E-03	4.15E-03
and	1.50E-04	0.00E+00	Methane	4.64E-03	4.74E-03
alohur	8.13E-02	4.74E-03	Methanol	3.00E-05	6.71E-04
Iranium ore	6.41E-04	4.20E-04	N.O	3.00E-05	3.00E-06
nervy Resources	BTUIL	BTU/Ib	NOx	1.38E-02	7.70E-03
loal	2.31E+03	5.15E+02	Organics	1.10E-04	1.80E-04
rude oil	1.20E+04	9.43E+03	PAH	0.00E+00	2.00E-05
Ivdro Energy	6.72E+02	6.39E+02	Particles	0.00E+00	1.30E-04
iznite	2.47E+01	0.00E+00	Phenol	2.00E-05	3.00E-07
latural gas	1.62E+04	1.73E+04	Provvlene	8.61E-04	1.07E-02
luclear energy	1.49E+03	1.20E+03	SO.	4.09E-03	2.20E-03
accounted energy	-3 59E+02	-2.10E±02	SOx	7.84E-03	3.26E-03
account and any	1b/lb	Ib/Ib	Formaldelande	0.00E+00	2.00E-06
Vood	1275-02	0.00E+00	Dimathylathar	0.00E+00	4 00E-06
io fail	3.605-04	0.0000+00	VOC	1 37E-03	2.005-05
liomass	1.50E-04	0.00E+00	Emission to Water	Iblb	16/16
merary	FWb/lb	kWb/lb	A13+	4 10E-05	0.00F+00
lectricity	8.09E-01	4 95E-01	BOD	1.89E-05	4 00E-06
low materials	њињ	њањ	Cd	7.51E-06	0.00E+00
allulose	0.0000+00	0.002+00	d-	3.05E-05	4 00E-04
ilicic acid	7.41E-02	0.0000+00	čo.	4 55E-05	0.00E+00
locidual moduct	6.61E-03	0.0000+00	con	1.21E-03	5.43E-04
assume product	BTUR	BTUR	Dissolved organics	1.29E-05	130E-05
	2.478401	0.0000+00	Disselved collide	6 20E-03	2.065-04
laetojoitu	2.472.401	0.002+00	Ensorted solids	0.002+00	2.002-07
When final	1.248+03	0.0000+00	H+	4 10F-05	3.30E-05
Vente	1.242.00	IL AL		5 10E 06	2.00E.06
varate brilding unate	2 105-04	1.008-04	Lug Hashaankaan	0.30E-06	0.005-00
concerning wasse	5.77E_02	5.248-03	Taylocaroons	9.39E-03	0.00E+00
Sandruotts Waste	3.772-05	6.705-03	Matela	1.13E-04	0.00E+00
nginy radioactive waste	2.00E-03	0.792-03	DUSCRIS No. 1	1.132-04	0.00E+00
anorui	7.832-03	1.77E-02	IN DODAL	1.11E-05	8.01E-05
lineral waste	8.26E-03	9.16E-03	Na+	4.92E-04	3.30E-05
luxed industrial waste	2.15E-03	5.90E-04	NaCl	5.41E-04	0.00E+00
ion hazardous waste	1.81E-01	3.64E-02	Oil and fat	4.25E-05	2.30E-05
lags and ash	2.17E-03	2.18E-03	Organic substance	3.57E-05	0.00E+00
ludge (dry matter)	1.65E-03	2.07E-03	Organics	2.06E-03	0.00E+00
Vaste to incineration	3.02E-03	2.10E-03	Phenol	4.70E-06	3.00E-07
Vaste to recycling	1.02E-03	3.60E-04	P-tot	2.90E-06	0.00E+00
			SO42	9.71E-04	1.47E-04
			Suspended solids	3.55E-03	8.88E-04
			Total organic carbon	2.34E-04	2.18E-04
			*		

Table 30 – LCI Adhesive Data Set (PRF)

- 0.312 lbs (PRF + Hardener) per cubic foot glulam/CLT

- Adhesive consists of 85% PRF resin & 15% hardener

Source: Puettmann & Wilson (2004, p.16)

# LCI Data Set - MUF and Hardener Adhesive

	MUF	Hardener		MUF	Hardener
lesources	lb/lb	lb/lb	Emissions to air	lb/Ib	lb/lb
lir	4.83E-02	9.89E-01	Aromatics	0.00E+00	1.90E-05
litrogen	3.05E-03	8.41E-03	CO	7.21E-04	3.03E-03
lauxite	4.40E-04	2.90E-04	CO <sub>2</sub>	1.44E+00	1.35E+00
ellulose	0.00E+00	1.12E-02	Dust	9.26E-04	1.42E-03
opper ore	1.36E-04	1.57E-03	HCOOH	0.00E+00	4.44E-04
ore ore	6.00E-05	2.10E-04	Hydrocarbons	2.13E-03	4.65E-03
eldspar	2.30E-04	0.00E+00	Methane	6.89E-03	2.52E-03
laolin	0.00E+00	2.99E-01	NH,	1.65E-04	0.00E+00
imestone	4.30E-04	7.81E-04	NrO	0.00E+00	2.30E-05
lethane	0.00E+00	2.20E-04	NO <sub>x</sub>	5.27E-03	9.06E-03
laC1	4.22E-03	2.30E-01	PAH	0.00E+00	1.60E-05
litrogen	0.00E+00	8.41E-03	Particles	0.00E+00	1.30E-05
alt	1.48E-03	6.26E-03	so,	2.49E-03	3.29E-03
	2.44E-03	9.01E-02	SO <sub>4</sub>	4.65E-03	4.25E-03
rona	0.00E+00	3.00E-04	Formaldehyde	2.00E-06	0.00E+00
Iranium ore	1.35E-04	1.27E-03	Dimethylether	2.00E-06	0.00E+00
nergy resources	BTUIL	BTU/Ib	Methanol	1.00E-04	2.40E-03
ito fuel	0.00E+00	2.56E+02	VOC	0.00E+00	5.65E-04
loal	7.44E+02	1.46E+03	Emissions to Water	lb/Ib	њль
rude oil	1.76E+03	9.17E+03	A13+	0.00E+00	5.00E-06
leavy oil	0.00E+00	7.42E+01	AOX	0.00E+00	2.10E-05
lydro energy	1.92E+02	1.15E+03	BOD	3.10E-05	1.80E-05
lydrogen.	1.24E+01	0.00E+00	Cd	0.00E+00	4.00E-06
ignite	5.98E+01	0.00E+00	CI-	0.00E+00	3.54E-03
latural gas	1.49E+04	1.19E+04	COD	1.24E-03	1.73E-03
inclear energy	1.81E+02	1.60E+03	Dissolved organics	0.00E+00	1.00E-05
ecovered energy	-1.32E+02	-4.21E+02	Dissolved solids	1.91E-04	6.49E-03
)ther fuel	0.00E+00	6.72E+02	Gypsim	0.00E+00	7.01E-05
Vood	6.19E+01	9.07E+01	H+	4.00E-05	2.602-05
nergy	RMP0P	kWh(lb	Hg	0.00E+00	5.00E-06
lectricity	2.46E-01	4.64E-01	Hydrocarbons	1.70E-05	5.80E-05
law materials	16/16	ID/ID	Lamestone	1.00E-05	0.00E+00
eliniose	2.40E-02	0.00E+00	Metzis	5.70E-05	1.182-04
Vaste	ID/ID	ID/ID	N total	3.40E-04	9.01E-06
uilding waste	7.01E-05	2.60E-04	Na+ Na+	5.09E-04	4.92E-04
iazardous waste	1.09E-02	1.54E-02	NACI	0.002+00	3.382-04
lightly radioactive waste	0.00E+00	3.00E-05	NR,	0.00E-00	1.00E-06
anonii	1.73E-02	3.30E-02	Oil and bax	4.40E-03	2.802-03
ow ramoactive waste	0.00E+00	0.002+00	P*000	0.002+00	1.002-06
illieral waste	7.41E-03	2.00E-05	310;	0.00E+00	1.202-03
inted indistrial waste	9.51E-04	9.21E-04	504° 8-+	0.00E+00	2.5/E-05
on mizardous waste	1.150-02	1.40E-01	Subshatar	0.00E+00	0.00E+00
lades and and	0.0000-000	2.105.02	Superior de des Vide	4 2012 04	2 212 02
runge Inden (den sommer)	0.00E+00	1.50E-03	Tatal assault carbon	1.89E-04	3.512-05
Gadge (dry minor) Paste to incineration	1.04E-03	1.02E-05	Total organic carbon	2.202-04	2.662-04
Varie to mending	3.538-03	3.00E-03			
rasie to recycling	3.332-03	3.322-03			
ource: Nilsson 2001					

Table 31 – LCI Adhesive Data Set (MUF)

- Adhesive consists of 90% MUF resin & 10% hardener

Source: Puettmann & Wilson (2004, p.17)

<sup>- 0.055</sup> lbs (MUF + Hardener) per cubic foot glulam/CLT

# **Heat of Combustion**

Fuel Source	Higher Heating Value (MJ/kg)
Wood (air dry)	19.0
Bituminous Coal	24.0
Diesel	46.2
Crude Oil	46.3
Liquid Propane	46.4
Natural Gas	53.6

### Table 32 – Higher Heating Values

	Global Warming Potential	<b>Acidification</b>	Eutrophication	Fossil Fuel Depletion	Water Intake	Criteria Air Pollutants	Ecological Toxicity	Human Health - Non Carcinogenic	Human Health - Carcinogenic	Ozone Depletion	<u>Smog</u>
	(g CO <sub>2</sub> eq.)	(millimoles $H^{+}$ eq.)	(g N eq.)	(MJ)	(L)	(MicroDALYs)	(g 2,4-D)	(g C <sub>7</sub> H <sub>8</sub> (toulene) eq.)	$(g C_6 H_6 (benzene) eq.)$	(g CFC-11 eq.)	(g NO <sub>x</sub> eq.)
Reinforced Concrete Frame											
Gypsum	40,265,274	17,011,835	13,575	80,396	21,181	6,018	132,487	45, 339, 654	36,341	0	113,303
Generic Steel Framing	14,337,410	3,602,166	3,411	15,050	113,864	619	201,873	683,424,615	471,907	0	43,579
R13 Insulation	3,813,058	4,060,622	5,010	16,737	21,566	1,444	62,509	36, 299, 372	25,316	0	29,989
Cast-in-place Concrete -15% Fly Ash	5,381,469,467	1,516,102,634	1,409,715	3,832,134	7,212,727	1,494,740	36,283,572	957,503,239,998	752,616,312	32	28,826,500
Curtain Wall	506, 784, 481	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
ccSPF Insulation	33,334,350	16,532,926	57,497	2,055	0	77,969	0	0	0	0	27,401
TOTAL - CONCRETE FRAME	5,980,004,039	1,557,310,183	1,489,207	3,946,372	7,369,338	1,580,790	36,680,441	958,268,303,639	753,149,876	32	29,040,772
Heavy Timber Frame											
Gypsum	40,265,274	17,011,835	13,575	80,396	21,181	6,018	132,487	45, 339, 654	36,341	0	113,303
Generic Wood Framing	1,187,906	268,177	596	982	3,423	138	6,242	18,826,565	13,221	0	4,813
R13 Insulation	1,705,743	1,816,489	2,241	7,487	9,647	646	27,963	16,238,254	11,325	0	13,415
Cast-in-place Concrete - 15% Fly Ash	3,597,714,370	1,019,665,080	935,233	2,562,826	4, 783, 683	1,017,340	24,130,452	647, 360, 700, 990	509,016,150	19	19,523,656
CLT - PRF & MUF Adhesives	-1,943,513,008	201, 123, 395	52,254	959,934	174,479	51,480	5,439,722	430,382,677	105,142	0	2,999,493
Glulam - PRF & MUF Adhesives	-472,234,002	100,580,740	32,884	566,944	58,089	51,048	413,955	16,347	3	0	1,324,509
Exterior Wood Sealer	647,577	2,532,755	19,162	10,917	206,528	663	51,806	3,112,721	2,832	0.0000	32,040
Curtain Wall	506, 784, 481	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Generic Cedar Siding	8,893,544	2,954,375	6,827	19,792	93,616	1,197	31,562	28, 279, 196	31,027	0	40, 346
TOTAL - TIMBER FRAME	1,741,451,886	1,345,952,846	1,062,772	4,209,278	5,350,648	1,128,529	30,234,190	647,902,896,402	509,216,040	19	24,051,575

 Table 33 – Cumulative LCIA Summary Data

	Non-Re	newable		Rene	wable	Fee	dstock	tock Fuel		<u>iel</u>
	Concrete	Timber		Concrete	Timber	Concrete	Timber		Concrete	Timber
Gypsum	577,087	577,087		95,524	95,524	76,211	76,211		595,777	595,777
Steel Framing	210,491	0		17,236	0	3,917	0		227,727	0
Wood Framing	0	10,537		0	34,496	0	29,798		0	15,302
Wood Sealer	0	84,707		0	180,922	0	196,289		0	68,492
R-13 Insulation	136,270	60,959		2,188	979	65,947	29,501		72,511	32,437
Concrete (15% fly ash)										
Slab-on-grade	1,646,484	1,646,484		869,566	869,566	714,712	714,712		1,800,897	1,800,897
Foundation Walls & Footings	6,448,512	6,448,512		51,075	51,075	41,573	41,573		6,455,639	6,455,639
Above grade walls & parapet	6,499,770	5,531,673		1,982,331	1,687,077	1,683,170	1,432,473		6,809,282	5,795,086
Beams, slabs, drop panel & slab bands	29,435,834	16,452,252		9,587,486	5,358,630	8,140,602	4,549,938		30,935,287	17,290,325
Columns	2,418,367	872,372		699,283	252,251	576,872	208,094		2,536,343	914,929
CLT Panels	0	5,896,557		0	49,721,848	0	46,495,236		0	9,123,169
Glulam	0	3,531,201		0	12,610,056	0	8,951,822		0	7,189,435
ccSPF	885,163	0		0	0	308,539	0		576,625	0
Cedar siding	0	153,798		0	327,657	0	367,778		0	113,677
Curtain Wall			3,931,322					3,931,322		
Total (not including curtain wall)	48,257,978	41,266,140		13,304,689	71,190,079	11,611,542	63,093,425		50,010,087	49,395,164
Total Concrete - Renewable + Non-renew.	65,493,989 Includes curto			les curtain	wall					
Total Timber - Renewable + Non-renew.		1	16,387,541							
Total Concrete - Feedstock + Fuel		Inclu	des curtain	wall				65 552 051		
Total Timber - Feedstock + Fuel							1	116,419,91	2	

# Table 34 – Cumulative Embodied Energy Summary (in MJ)