COMPARISON OF ENVIRONMENTAL PERFORMANCE OF A FIVE-STOREY BUILDING BUILT WITH CROSS-LAMINATED TIMBER AND CONCRETE

Submitted to

Sustainable Building Science Program

By

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

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EXECUTIVE SUMMARY

Cross Laminated Timber (CLT), which is made by laminating dimension lumber at right angles, is an innovative high-performance building material that offers many positive attributes including renewability, high structural stability, storage of carbon during the building life, good fire resistance, possibility of material recycling and reuse. It is conceptually a sustainable and cost effective structural timber solution that can compete with concrete in non-residential and multi-family mid-rise building market. Therefore, there is a need to understand and quantify the environmental attribute of this building system in the context of North American resources, manufacturing technology, energy constraints, building types, and construction practice. This study is to compare energy consumption of two building designs using different materials, i.e. CLT and concrete.

The designs were based on a five-storey office building, Discovery Place-Building 12, which is located in Burnaby, British Columbia, at 4200 Canada Way. The existing building was built with reinforced concrete. Embodied energy was calculated based on the total amount of material required for each of the building systems. Operational energy was calculated using eQUEST, an energy usage modeling software tool. The environmental impacts of the buildings were evaluated by comparing the total energy consumption through the building life.

CLT has lower non-renewable energy consumption compared to concrete in terms of material acquisition, manufacturing and transportation. Previous studies shew that operational energy accounts for the main amount of total energy use in buildings during their service life. Hence, the importance of embodied energy increases by reducing operational energy consumption. CLT has lower embodied energy compared to concrete. Therefore, the advantage

of using CLT as a construction material is becoming greater by designing low energy or passive buildings.

INTRODUCTION

Climate change is probably the most important and urgent issue facing mankind. Reducing greenhouse gas emissions, particular CO_2, is becoming an increasingly important issue. According to the statistical report of IEO 2007 [3] the building sector in developed nations is accounting for about 40% of atmospheric emissions including greenhouse gases, 40% of primary energy consumption, and 70% of electricity use [4]. The break-up of energy consumption for these sectors in accordance to the International Energy Agency (IEA) statistics is shown in Figure 1 [4]. The significant amounts of energy consumption that is associated with buildings could be a major cause of negative impacts on the environment in the present and long term.

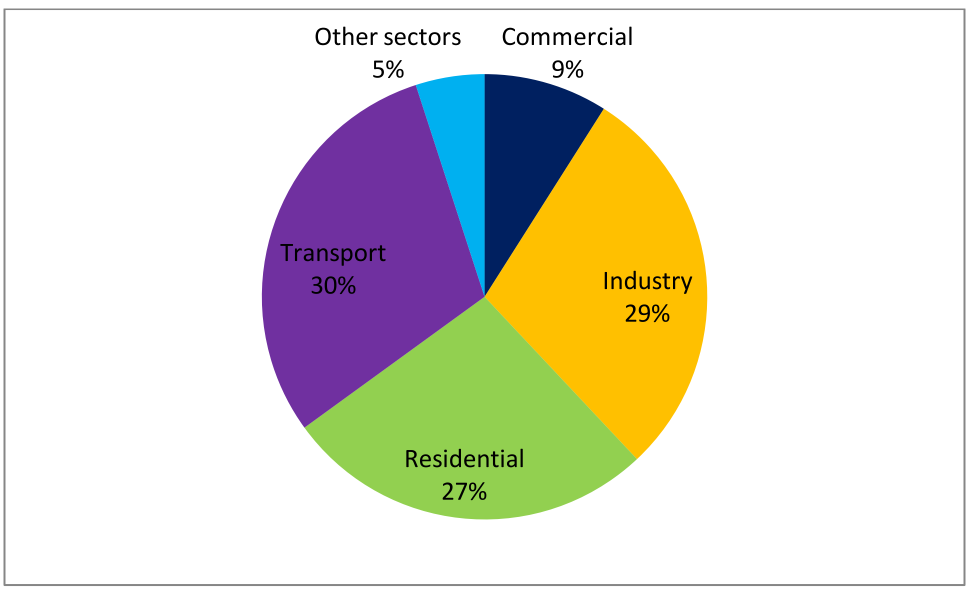


Figure 1 Energy consumption break-up by sector wise [4].

Buildings and the environment are intrinsically linked and connected through a variety of direct and indirect interactions. Sustainable building science is crucial to the success of minimizing the impact of the built environment on the natural world from the design, construction, commissioning, operation and maintenance of buildings. The practice of sustainable building design must therefore consider establishment of harmony between the building material, the building system and their impact to the environment and the surrounding natural landscapes.

Development of new building systems with renewable material that can store carbon during its service life, in which innovative structural materials are most efficiently applied, plays a very important role to popularize sustainable and cost effective buildings. Cross-laminated timber (CLT), an innovative value-added engineered wood product, provides a sustainable alternative to steel and concrete construction. Therefore, there is a need to understand and quantify the environmental attribute of this building system in the context of North American resources, manufacturing technology, energy constraints, building types, and construction practice.

Sustainable building, which refers to a structure and using process that is environmentally responsible and resource-efficient throughout a building's life cycle, is one of the most interesting slices of the market and has a very stable growth rate. By discussing energy performance of the innovative CLT building system and quantifying the environmental impact compared to the existing concrete system of a case study building, this study can help the architect, engineering and construction industry create better, more sustainable buildings in the future.

CROSS-LAMINATED TIMBER

CLT is a growing phenomenon and a recent building solution alternative in timber construction in North America. This material is manufactured using low-grade timber off-cuts, and then jointed in cross layers with either glue or mechanical connections. An odd number of crosswise assembled layers (3, 5, 7, 9…) guarantee structural integral stability and the arrangement of the lengthwise and crosswise wood members helps to increase dimensional stability considerably (Figure 2). Swelling and shrinkage are minimized due to the cross lamination effects and the manufacturing processes.

Figure 2 Layout of a 3-ply CLT panel.

CLT can be employed in the construction of a wide variety of structural elements, for example,

- structural and non-structural wall elements
- multi-storey structures with or without concrete sub-structure
- solid partitions with or without linings
- floor/ceiling, parapet wall and roof elements
- pre-insulated wall and roof cassettes
- cantilevered floors/balconies
- load bearing lift shafts
- stairs

Depending on its intended use, CLT can be used for either visible or hidden construction applications. Combined with other engineered wood products, such as glulam and laminated veneer lumber (LVL), CLT demonstrates great potential of serving as crucial elements in the construction of buildings made entirely from timber.

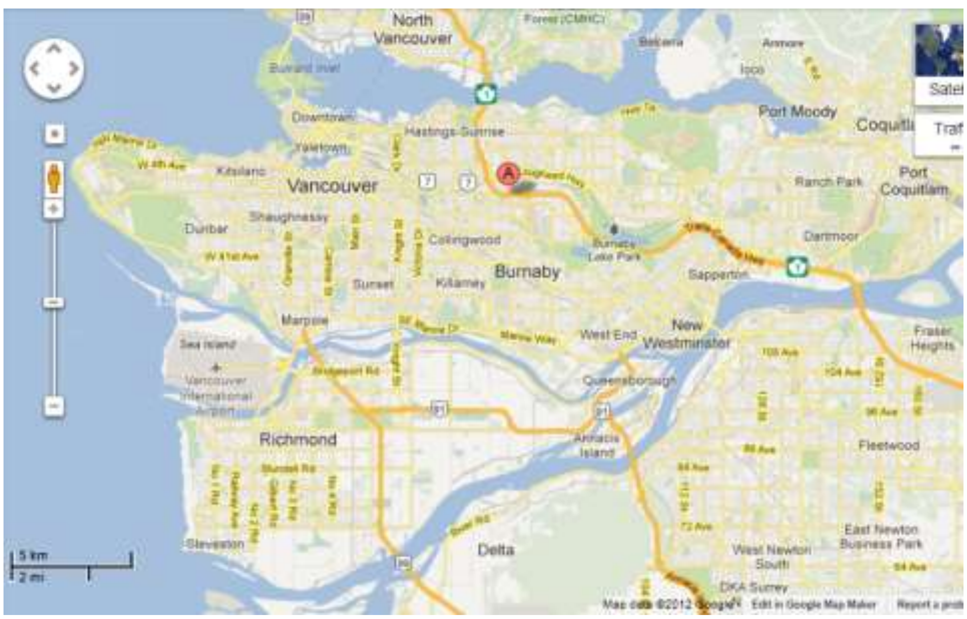
CLT offers a wide variety of advantages in terms of structure, environment, economy, utility, and architectural design. It is conceptually a sustainable and cost effective structural timber solution that can compete with concrete in non-residential and multi-family mid-rise building market.

DISCOVERY PLACE-BUILDING 12

The Discovery Place - Building 12, which is located at 4200 Canada Way in Burnaby, British Columbia, was selected as an example for this study (Figure 3). This 152,068 ft^2 commercial use office building is part of a large research center focusing on environmental and natural concerns. The architectural and structural design was prepared by Bunting Coady Architects and Read Jones Christoffersen Consulting Engineers (RJC), respectively. The mechanical and electrical design was prepared by Cobalt Engineering. This building is a certified LEED-CS v2 platinum[1] project.

[1] LEED for Core and Shell is a green building rating system for designers, builders, developers and new building owners who want to address sustainable design for new core and shell construction. Core and shell covers based building elements such as structure, envelope and the HVAC system. LEED for Core and Shell Development certification are awarded according to the following scale: certified, silver, gold, and platinum [6].

(a) Source: Enersolv Design + Build Ltd.



(b) Source: Google map.

Figure 3 Discovery place-building 12.

BUILDING REDESIGN

The building was built with reinforced concrete structure, which was explained in detail by Robertson [5]. To compare the environmental impacts of the building throughout its life cycle, the first step was to redesign the structure using laminated timber, i.e. CLT and glulam, system. The new design, which was conducted in accordance with CSA Standard O86, Engineering Design in Wood [2], was functionally equivalent to the original design. Note that this redesign is different in some significant ways from the previous work by Robertson [5]. The concrete slabs in floor and roof systems were replaced by T-slabs which consisted of CLT panels and glulam beams. The concrete beam and shear wall were replaced by glulam beam and CLT wall, respectively. Design procedures for selected structural members are shown in the following sections.

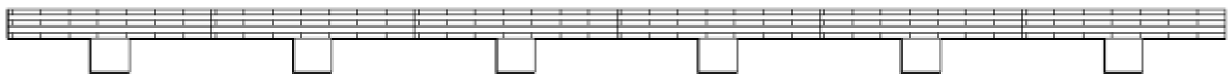
Redesign of T-slabs

According to the structural design conducted by RJC, the specified uniform loads are listed in Table 1.

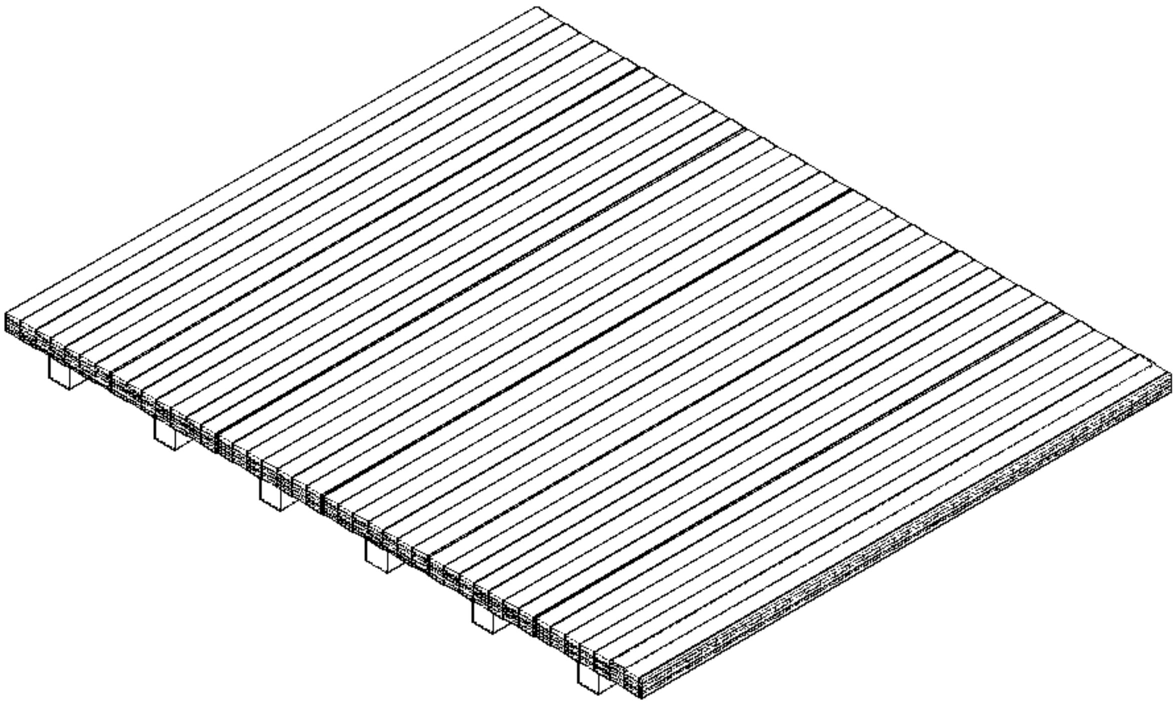
Table 1 Details of design loads.

Location		Live load	Superimposed dead load (SDL)
Roof -	based on a ground snow load	54.3 psf (2.6 kPa)	25 psf (1.2 kPa)
	plus a rain load	12.5 psf (0.6 kPa)	25 psf (1.2 kPa)
Office floors		65 psf (3.1 kPa)	25 psf (1.2 kPa)

Assume the T-slabs consisting of 5-ply CLT panels with a thickness of 140 mm and 175 mm × 190 mm glulam beams as shown in Figure 4. The total load on a T-slab with a width of 1000 mm can be calculated as follows.



(a)



(b)

Figure 4 T-slab system consisting of 5-ply CLT panels and glulam beams.

Load:

Self-weight:

$$(500\ kg/m^3 \times g \times 1m \times 0.14m \times L + 500\, kg/m^3 \times g \times 0.175m \times 0.19m \times L)/(1m \times L) =$$

$$849\, N/m^2 \approx 1\ kPa$$

Specified dead load:

$$1.2\ kPa + 1\ kPa = 2.2\ kPa$$

Specified live load (roof):

$$2.6\ kPa + 0.6\ kPa = 3.2\ kPa$$

Total specified load (roof):

$DL + LL = 2.2\ kPa + 3.2\ kPa = 5.4\ kPa$

Total factored load (roof):

$1.25DL + 1.5LL = 1.25 \times 2.2\ kPa + 1.5 \times 3.2\ kPa = 7.55\ kPa$

Specified live load (floor): $3.1\ kPa$

Total specified load (floor):

$DL + LL = 2.2\ kPa + 3.1\ kPa = 5.3\ kPa$

Total factored load (floor):

$1.25DL + 1.5LL = 1.25 \times 2.2\ kPa + 1.5 \times 3.1\ kPa = 7.4\ kPa$

Moment resistance

$$N.A. = \frac{1000\ mm \times 140\ mm \times 70\ mm + 175\ mm \times 190\ mm \times (140\ mm + 190\ mm/2)}{1000\ mm \times 140\ mm + 175\ mm \times 190\ mm}$$

$$\approx 102\ mm$$

$$I = \frac{1000\ mm \times (140\ mm)^3}{12} + 1000\ m \times 140\ mm \times \left(N.A. - \frac{140\ mm}{2}\right)^2 + \frac{175\ mm \times (190\ mm)^3}{12} + 175\ mm \times 190\ mm \times \left(140\ mm + \frac{190\ mm}{2} - N.A.\right)^2 = 1060 \times 10^6\ mm^4$$

$S = I/c = I/(140\ mm + 190\ mm - N.A.) = 4.64 \times 10^6\ mm^3$

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

where

$\varphi = 0.9$

$F_b = f_b(K_D K_H K_{Sb} K_T)$

$f_b = 23.9\ Mpa$ (Class E2 CLT according to APA Standard)

$K_D = 1.00$ (Load duration factor, standard term)

$K_H = 1.10$ (System factor)

$K_{Sb} = 1.00$ (Service condition factor, bending at extreme fibre, dry service conditions)

$K_T = 1.00$ (Treatment factor)

$F_b = 23.9\ Mpa \times 1.00 \times 1.10 \times 1.00 \times 1.00 = 26.3\ MPa$

$K_x = 1.00$ (Curvature factor, straight members)

$K_{zbg} = 1.03(BL)^{-0.18} \leq 1.0$

$B = 0.14\ m$ (Width of the widest piece for CLT)

$L = 7.92\ m$ (Length of beam segment from point of zero moment to point of zero moment)

$K_{zbg} = 1.03(0.14\ m \times 7.92\ m)^{-0.18} = 1.01 > 1.0 \rightarrow K_{zbgCLT} = 1.0$

$M_{r1} = 0.9 \times 26.3\ Mpa \times 4.64 \times 10^6\ mm^3 \times 1.00 \times 1.00 = 109.9\ kN \cdot m$

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

$S_2 = I/C_2 = I/(N.A.) = 10.39 \times 10^6\ mm^3$

$C_B = \sqrt{L_e d/b^2} = \sqrt{1.92 \times 7925\ mm \times 140\ mm/(1000\ mm)^2} = 1.46 < 10 \rightarrow K_{LCLT} = 1.0$

$M_{r2} = 0.9 \times 26.3\ Mpa \times 10.39 \times 10^6\ mm^3 \times 1.00 \times 1.00 = 245.9\ kN \cdot m$

$M_r = 109.9\ kN \cdot m$

$M_{froof} = (total\ factored\ load) \times L^2/8 = 59.20\ kN \cdot m$

$M_{froof} < M_r$

Factored shear resistance

$V_r = \varphi F_v 0.48 A K_N C_v Z^{-0.18}$

$\varphi = 0.9$

$F_v = f_v(K_D K_H K_{Sv} K_T)$

$f_v = 1.9\ MPa$ (Class E2 CLT according to APA Standard [1])

$K_{Sv} = 1.00$ (Service condition factor, longitudinal shear, dry service conditions)

$F_v = 1.9\ MPa \times 1.00 \times 1.10 \times 1.00 \times 1.00 = 2.1\ MPa$

$A = 1000\ mm \times 140\ mm + 175\ mm \times 190\ mm = 173250\ mm^2$

$K_N = 1.00$ (Notch factor, not notched)

$C_v = 3.69$ (Shear load coefficient)

$Z = A \times 7925\ mm = 1.37\ m^3$

$V_r = 0.9 \times 2.1\ Mpa \times 0.48 \times 173250 \times 1.00 \times 3.69 \times 1.37^{-0.18} = 545.2\ kN$

$V_{froof} = (total\ factored\ load) \times L/2 = 29.9\ kN$

$V_{froof} < V_r$

Maximum deflection under specified loads:

For $L/180$ deflection limit based on total load

$E_S I_{REQ'D} = 180[5wL^3/384] = 180[5 \times 5.4\ kPa \times (7925\ mm)^3/384] = 6.3 \times 10^6\ N \cdot m^2$

$E_S I_{ACTURAL} = 10300\ MPa \times 1060 \times 10^6\ mm^4 = 10.9 \times 10^6\ N \cdot m^2$

$E_S I_{ACTURAL} > E_S I_{REQ'D}$

For $L/360$ deflection limit based on live load

$E_S I_{REQ'D} = 360[5w_L L^3/384] = 360[5 \times 3.2\ kPa \times (7925\ mm)^3/384] = 7.5 \times 10^6\ N \cdot m^2$

$E_S I_{ACTURAL} > E_S I_{REQ'D}$

Design of T-slabs used in flooring followed the same procedures as described in the above calculations. In the case of different spans, the dimensions of glulam consisted in T-slabs were adjusted accordingly, e.g. 190 mm × 228 mm or 190 mm × 266 mm.

Redesign of wall elements

Using 3-ply CLT panels with a thickness of 102 mm as wall elements, the factored compressive resistance parallel to grain is

$P_r = \varphi F_c A K_{zcg} K_c$

where

$\varphi = 0.8$

$F_c = f_c(K_D K_H K_{Sc} K_T)$

$f_c = 18.1\ MPa$ (Class E2 CLT according to APA Standard [1])

$F_c = 18.1\ MPa \times 1.00 \times 1.10 \times 1.00 \times 1.00 = 19.9\ MPa$

$A = 68\ mm \times 1000\ mm = 68000\ mm^2$

$Z = 1000\ mm \times 102\ mm \times 3962\ mm = 0.404\ m^3$

$K_{zcg} = 0.68(z)^{-0.13} = 0.68(0.404)^{-0.13} = 0.765 < 1.0 \rightarrow K_{zcg} = 0.765$

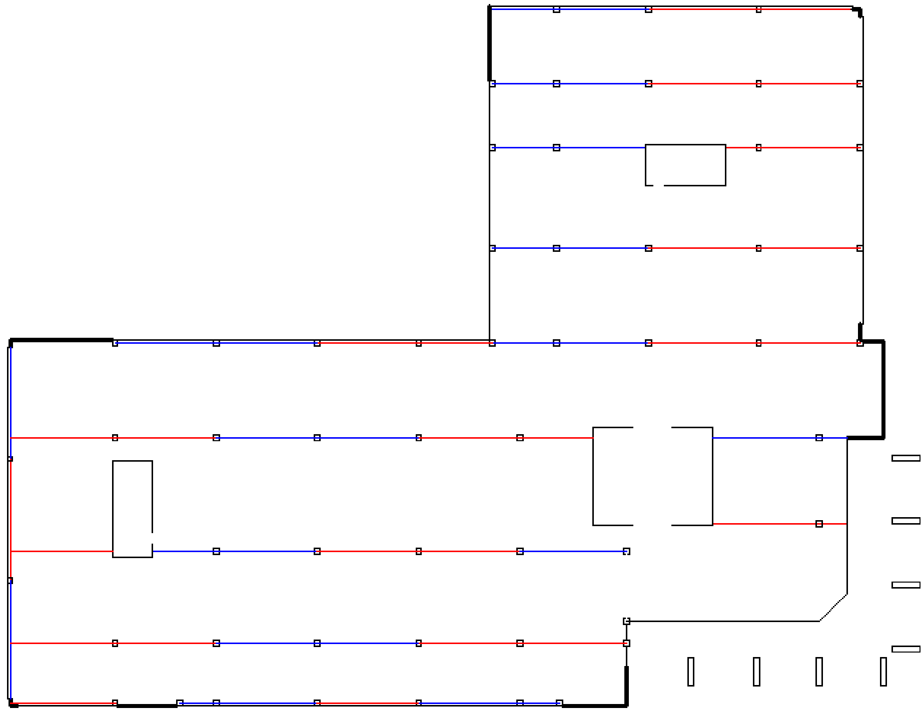
$$K_c = \left(1.0 + \frac{F_c K_{zcg} C_c^3}{35 E_{05} K_{SE} K_T}\right)^{-1} = \left(1.0 + \frac{19.9\ MPa \times 0.765 \times (3962\ mm/102\ mm)^3}{35 \times 0.87 \times 10300\ MPa \times 1.00 \times 1.00}\right)^{-1}$$
$$= 0.26$$

$P_r = 0.8 \times 19.9\ MPa \times 68000\ mm^2 \times 0.765 \times 0.26 = 215.4\ kN$

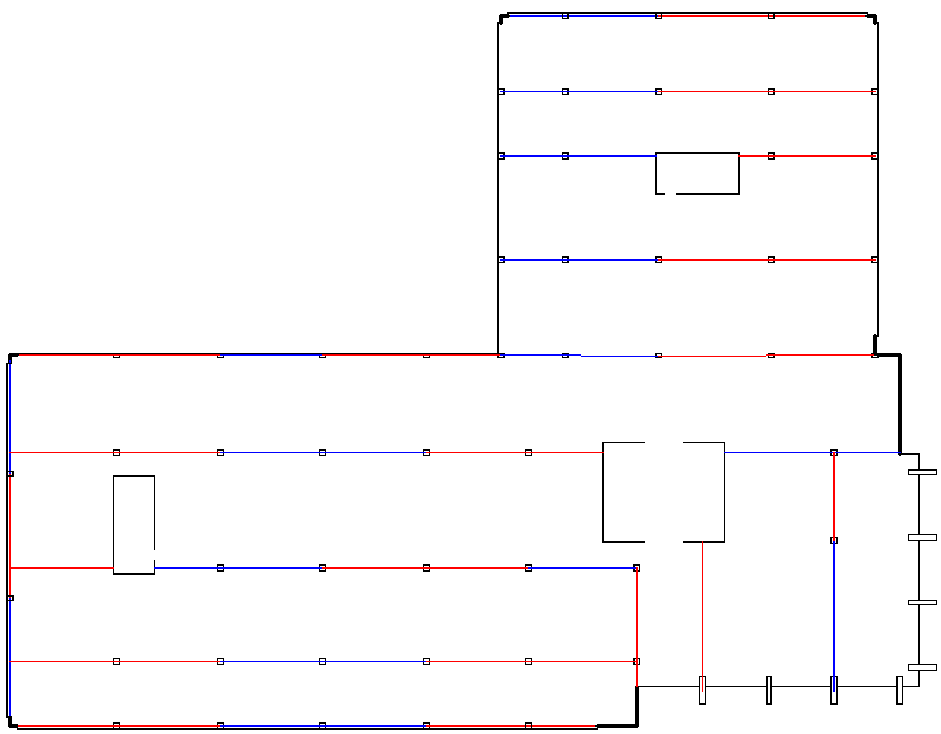
Redesign of glulam beams

The design of glulam beams were conducted using the software WoodWorks® produced by the Canadian Wood Council. 20f-EX 365 mm × 570 mm D-Fir (L) glulam was chosen in most of the cases while the thickness of the beam could be up to 950 mm.

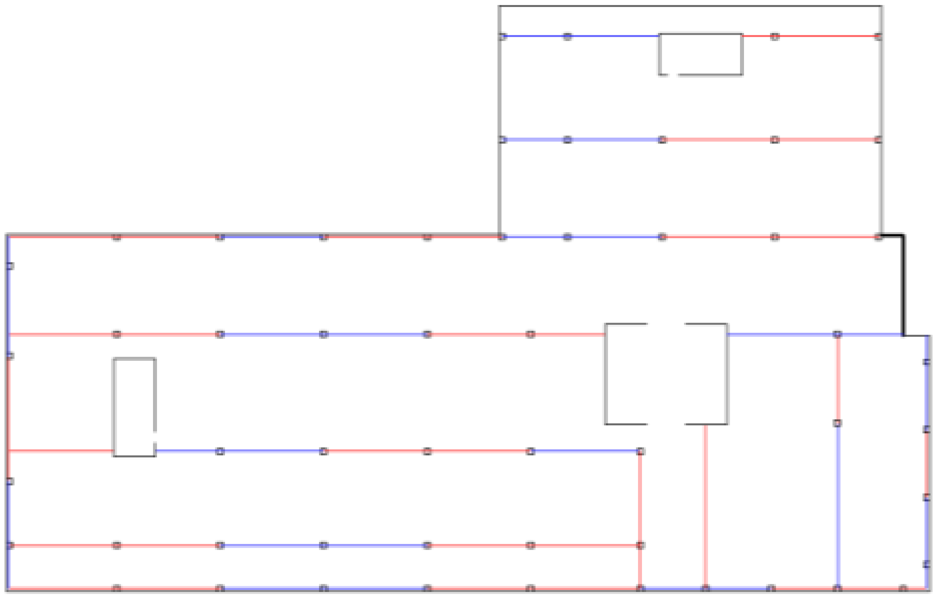
The redesign of the floor plans is shown in Figure 5, where the red and blue lines represent glulam beams; bold black lines represent exterior above grade concrete walls; regular black lines represent vertical curtain wall systems. T-slabs, which are not shown in this figure, are placed on top of the glulam beams.



(a) 2nd floor plan.



(b) 3rd and 4th floor plan.



(c) 5th floor and roof plan.

Figure 5 Redesigned floor plans.

The structural engineered wood members which were needed to replace the reinforced concrete components are summarized in Table 2.

Table 2 Volume of engineered wood members.

CLT	Volume (m^3)	Glulam	Volume (m^3)
T-slab	1958.2	T-slab	482.2
Wall	81.7	Beam	546.4
Column	36.9	Column	113.6
Total	2076.8	Total	1142.1

ENERGY CONSUMPTION

Embodied energy

According to Canadian Architect, Canada's only monthly design publication for architects and related professionals practicing in Canada, there are two forms of embodied energy in buildings.

- Initial embodied energy represents the non-renewable energy consumed in the acquisition of raw materials, their processing, manufacturing, transportation to site, and construction. The initial embodied energy can further be subdivided into two parts:

  Direct energy: The energy used to transport building products to the site and then construct the building.

  Indirect energy: The energy used to acquire, process, and manufacture the building materials, including any transportation related to these activities.
- Recurring embodied energy is the non-renewable energy consumed to main, repair, restore, refurbish or replace materials, components or systems during the life of the building.

This study will focus on the initial embodied energy consumption. The total initial energy consumption to construct the building using reinforced concrete or laminated timber systems is shown in Figure 6. Compared to reinforced concrete, laminated timber system could save about 18% of non-renewable energy. In Figure 7, timber structure had similar process energy to but over 300% higher feedstock energy than the reinforced concrete structure. CLT and glulam materials accounted for 84% of the total feedstock energy in the timber building system as shown in Figure 8. The environmental impact is shown in Figure 9 and Table 3.

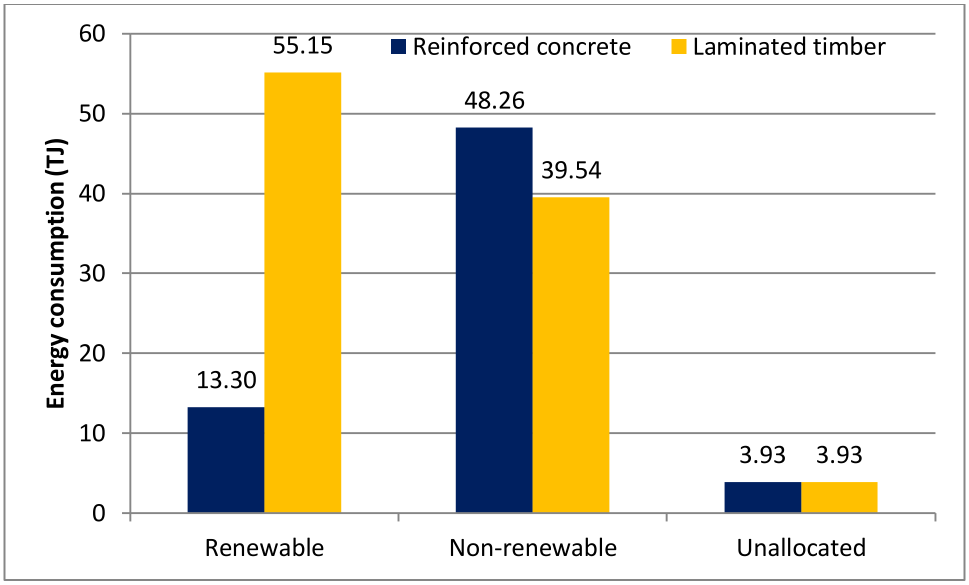


Figure 6 Total initial energy consumption of different building systems.

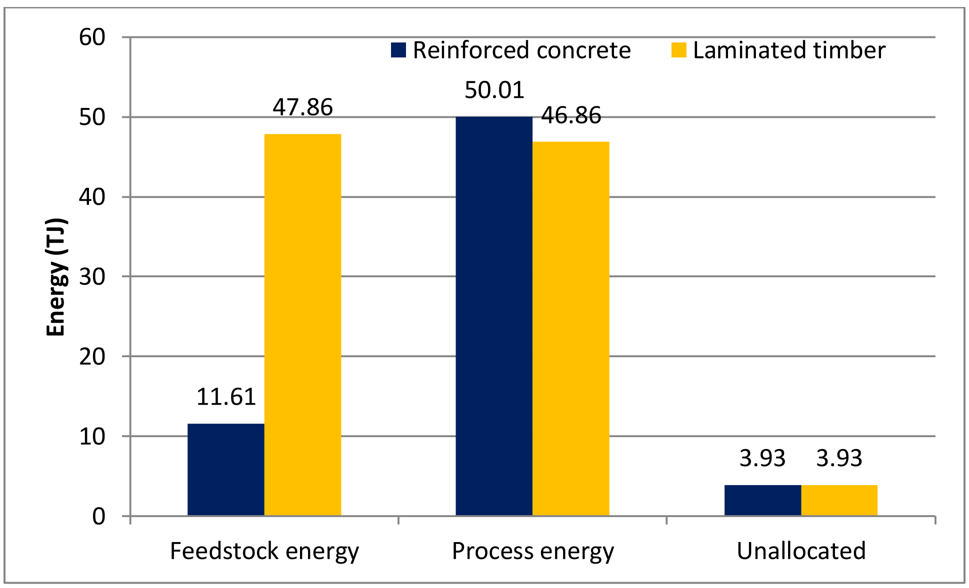


Figure 7 Primary energy of building materials.

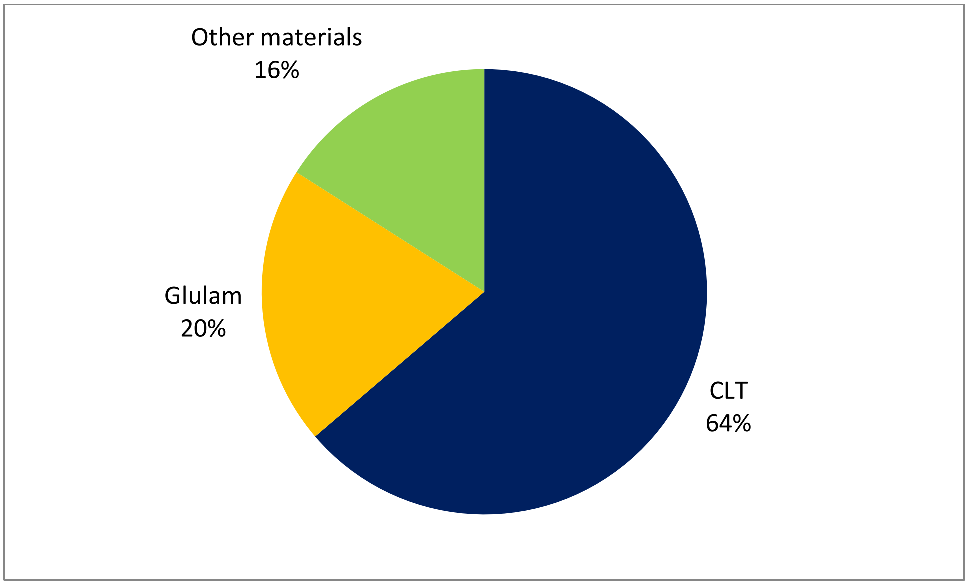


Figure 8 Feedstock energy contribution in the laminated timber building system.

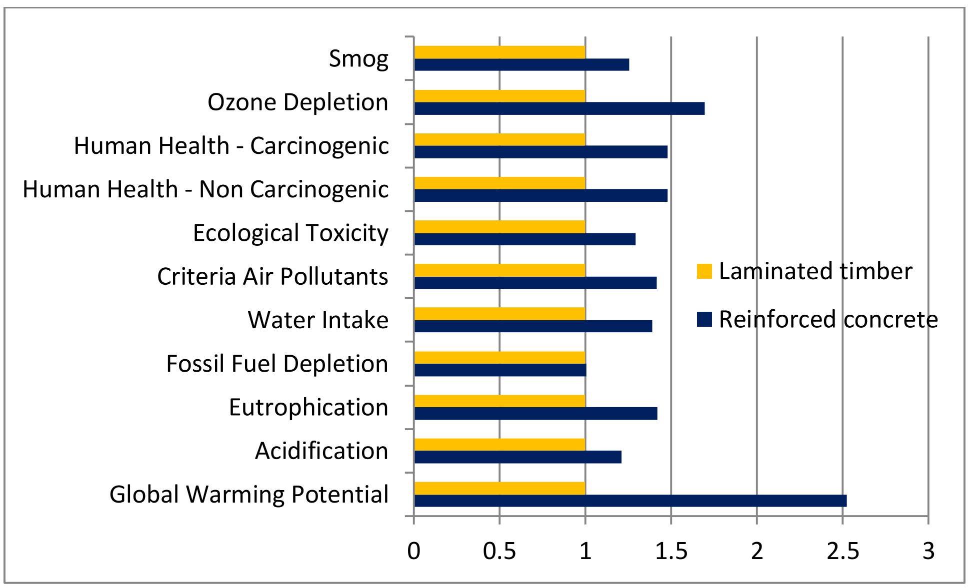


Figure 9 Normalized life cycle (from cradle to gate) environmental impact of different building systems.

Table 3 Environmental impact of different building systems.

	GWP (tonnes CO_2 equivalent)	Acidification (kmol H^+ equivalent)	Eutrophication (kg N equivalent)	Fossil Fuel Depletion (GJ)	Water Intake (1000L)	Criteria Air Pollutants (1000 MicroDALYs)
Reinforced concrete	5,980	1,557	1,489	3,946	7,369	1,581
Laminated timber	2,370	1,285	1,048	3,927	5,296	1,115
	Ecological Toxicity (kg 2,4-D)	Human Health - *Non Carcinogenic* (tons C_7H_8 (toulene) equivalent)	Human Health - *Carcinogenic* (tons C_6H_6 (benzene) equivalent)	Ozone Depletion (g CFC-11 equivalent)	Smog (kg NO_x equivalent)	\
Reinforced concrete	36,680	958,268	753	32	29,041	\
Laminated timber	28,398	647,755	509	19	23,132	\

Operational energy

The operational energy analysis was performed using the eQUEST version 3.64 building energy simulation software, based on the DOE-2.2 simulation engine. eQUEST is supported as a part of the Energy Design Resources program which is funded by California utility customers and administered by Pacific Gas and Electric Company, San Diego Gas & Electric, and Southern California Edison, under the auspices of the California Public Utilities Commission. It consists of a building creation wizard, an energy efficiency measure (EEM) wizard, and graphical reporting with a simulation engine derived from DOE-2.2. DOE-2.2 is the latest microcomputer version of DOE-2, which is a program designed to determine the energy consumption behavior of proposed and existing buildings utilizing an hour-by-hour simulation procedure. Although every effort has been made to model the actual building conditions, the calculated operational energy consumption may differ from reality because of assumptions of operating conditions due to lack of information and details.

A computer model was developed based on design plans of the building and the EEM of this specific design was evaluated.

Model input description

Building type: office

Building area: 152,068 ft^2

Location: Vancouver, BC, Canada

Code & Version: LEED-NC - v3.0

Heating source: electric and other

Cooling source: DX Coils; Heating source: DX Coils (Heat pump)

Table 4 to Table 10 describe some import inputs of the model. The HVAC system was modeled to operate during any occupied hours as shown in Table 6. Air ventilation varied by space occupancy as summarized in Table 9.

Table 4 Building envelope Summary.

Component	Material	Insulation
Roof	8 in concrete	3 in polyurethane (R-18)
Wall	8 in HW concrete	R-13 mtl furred insul
Floor	8 in concrete	2 in polyurethane (R-12)
Windows	Double 6 mm glass	U = 0.47, SHGC = 0.4

Table 5 Dimension of the case study building.

	Area (ft^2)	Floor to floor height (ft)	Floor to ceiling height (ft)
Ground floor	29036	13	9
2nd floor	29957	13	9
3rd floor	31823	13	9
4th floor	31823	13	9
5th floor	29429	13	9

Table 6 Building operation schedule.

	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday	Holiday
Open at	7 am	7 am	7 am	7 am	7 am	8 am	8 am	Closed
Close at	6 pm	6 pm	6 pm	6 pm	6 pm	5 pm	5 pm	Closed

Table 7 Ground floor interior lighting loads.

Area type	Office (open plan)	Restroom	Corridor	Lobby (office reception/waiting area)	Mechanical/electrical room	All others
Lighting (W/ft^2)	1.10	0.90	0.50	1.30	1.50	0.50

Table 8 Miscellaneous loads.

Area type	Office (open plan)	Restroom	Corridor	Lobby (office reception/waiting area)	Mechanical/electrical room	All others
Electric load (W/ft^2)	0.75	0.10	0.00	0.25	0.10	0.10
Sensible ht (frac)	1.00	1.00	1.00	1.00	1.00	1.00

Table 9 Activity areas allocation.

Area type	Office (open plan)	Restroom	Corridor	Lobby (office reception/waiting area)	Mechanical/electrical room	All others
Design max. occup (sf/person)	200	100	100	7	333	100
Design ventilation (CFM/per)	17	15	15	15	50	15

Table 10 Seasonal thermostat setpoints.

Occupied (°F)		Unoccupied (°F)	
Cool	Heat	Cool	Heat
76.0	70.0	82.0	64.0

The model incorporated a tank-type domestic water heater fueled with electricity with an energy factor of 0.91 and an entering water temperature of 135 °F. The final eQUEST model is shown in Figure 10.

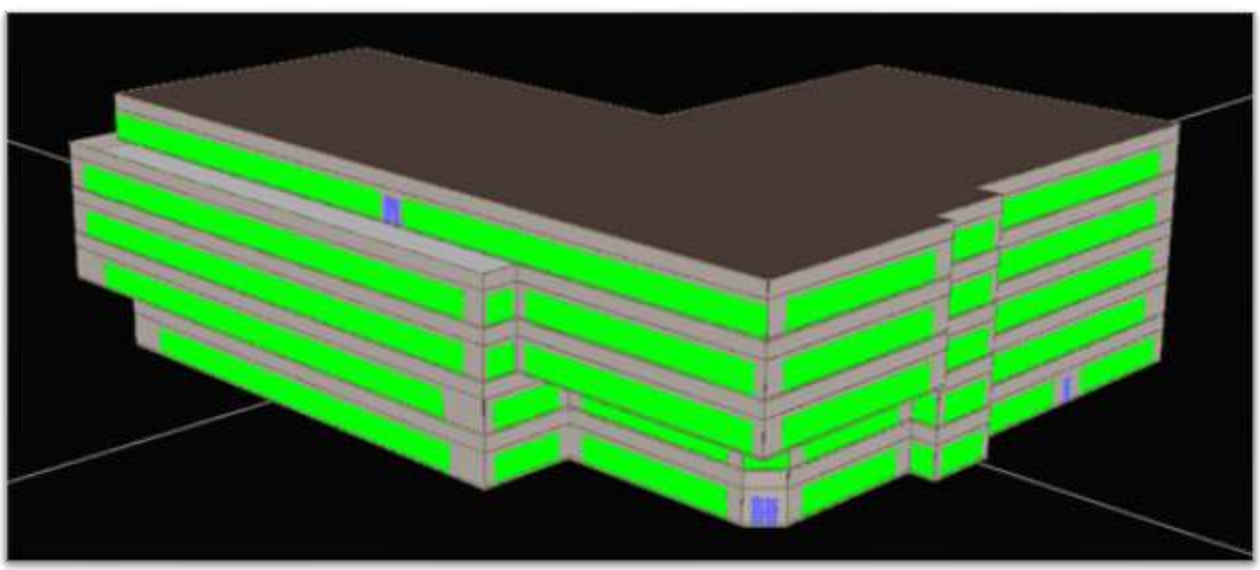


Figure 10 eQUEST model of the case study building.

RESULTS AND DISCUSSIONS

From the analysis, the annual energy consumption of the building is 1,731,973 kWh. August and December consume more energy than the other months, as shown in Figure 11, because of higher demand of space cooling and heating. April has the least energy requirement followed by February. Considering the whole year, miscellaneous equipment is responsible for the highest percentage of energy consumption as shown in Figure 12. Area lighting took the second place with a percentage of 30%. Space heating and cooling represents only 12% and 10%, respectively, of the total energy consumption due to the mild weather in Vancouver.

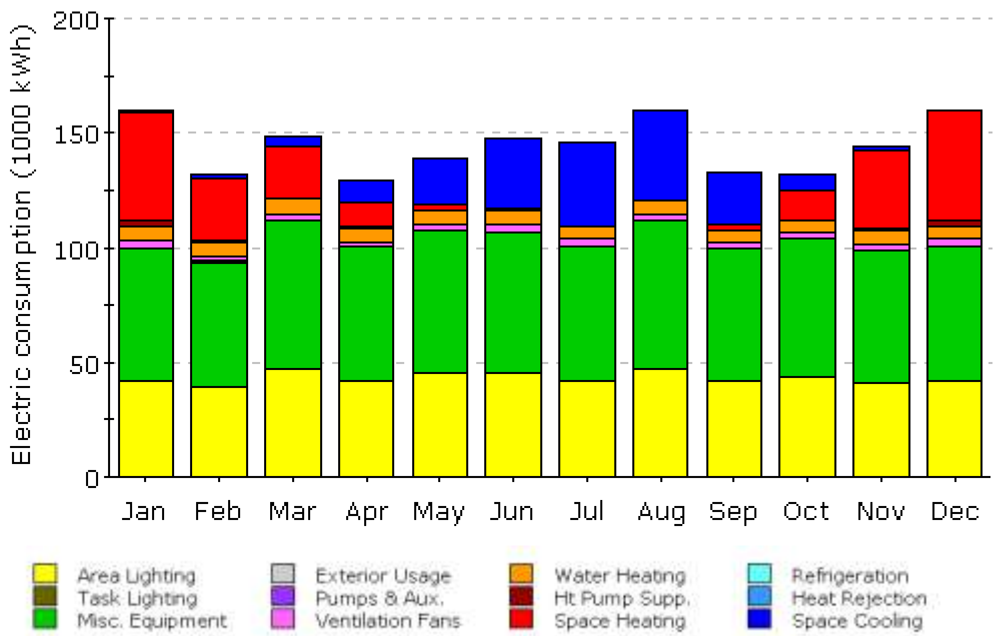


Figure 11 Monthly operational energy consumption by end-use.

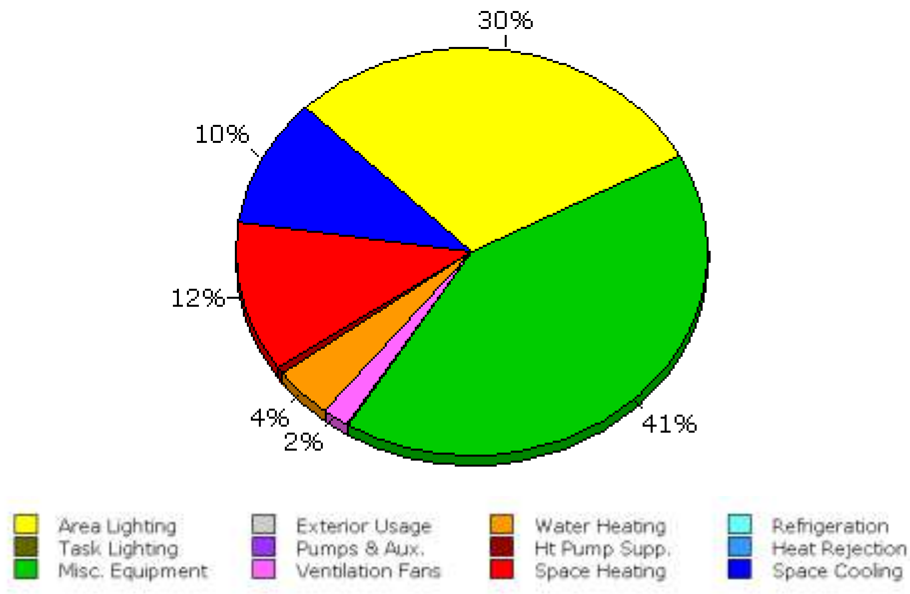


Figure 12 Annual operational energy consumption by end-use.

The embodied energy of the building using laminated timber structure and concrete structure is 10,983,333 kWh and 13,405,556 kWh, respectively. Assume the lifespan of the building to be 30 years, the total operational energy required will be 51,959,190 kWh. The ratio of operational energy to embodied energy for laminated timber and concrete building systems is 4.7 and 3.9, respectively. By using laminated timber system, energy saving during the lifetime of the building is about 4.66% of its total operational energy consumption. This percentage could increase by reducing operational energy consumption through improved technology and design. In other words, the benefits associated with using laminated timber over concrete building system are increasing through design optimization associated with lower operational energy demands.

CONCLUSIONS

Both embodied and operational energy were calculated for a five-storey office building built with different materials, i.e. CLT and concrete. Over the building life period, wood embodies and consumes less energy compared to concrete. The benefits associated with using laminated timber over concrete building system are increasing through design optimization associated with lower operational energy demands. This study will provide a deep insight of the environmental advantages of CLT and lay a solid foundation for creating better and more sustainable buildings in the future.

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