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Article

A Comparison of Life Cycle Impact of Mass Timber and Concrete in Building Construction

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Abstract: Life cycle assessment, LCA is one of the tools that is used to measure the environmental impacts of a process or an operation. Various studies have mentioned the benefits of mass timber in building construction. This study presents an evaluation of the LCA of certain mass timber in relation to concrete-based materials. Using Athena impact estimator for buildings, the study compared the results of an LCA study for a house that is designed with concrete beams, concrete columns, and concrete walls with brick in the envelope category (Material group 1) with those that are made with glulam beams, glulam columns, CLT walls with spruce wood bevel siding (Material group 2), and another building with LVL columns, LVL beams, CLT walls with spruce wood bevel siding (Material group 3). The results are in line with those that were reported by the majority of previous researchers. For the location that is being reviewed (Calgary, Alberta), the designs showed that construction with wood materials having mass timber components will have a better environmental performance than that for a building design with more concrete-based materials. The building design with more concrete-based material (group 1) showed 242% and 60% higher global warming and acidification potential respectively than the building with glulam beams and columns (material group 2). Except for ozone depletion potential, material group 2 (with glulam beams and columns) has a lower impact than material group 3 (with LVL/PSL beams and columns). The differences in impacts are more pronounced when the comparison is with design with more concrete-based products. This report further shows that LCA can be helpful during the preliminary design to evaluate the expected environmental impacts of the choice of different materials. This study recommends that material manufacturers and building contractors pay attention to LCA results to evaluate areas for continuous improvement.

Keywords: Mass Timber; Concrete Materials; Building Design; Construction; Environmental Impacts; Life Cycle Assessment; Laminated Veneer Lumber; Glulam; CLT

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1. Introduction

The construction industry has attracted a great deal of attention in the efforts to reduce environmental impacts from industrial operations. Buildings are one of the highest environmental impactors, as they consume large quantities of materials and energy [1]. Concerns about the environmental impacts of construction necessitate a review of how we can best ensure that our buildings are constructed in the most environmentally friendly manner. Efforts to reduce the environmental impacts of construction involve analysis of the impact of various construction materials as well as analysis of how processes can be optimized to reduce environmental footprints. Both wood and concrete building construction has been around for a long time. With the development of tall wood buildings in recent years, mass timber panels have gained lots of popularity. Due to its low environmental impact, and being a generic material, timber building has attracted increased attention globally [2]. Increased use of multi-story timber buildings has the potential to create a significant reduction in the life cycle environmental impact of a building [3]. A previous study [4] noted that if 100% of residential building structures were to be constructed with engineered wood products, EWP instead of reinforced concrete, a saving of 26 Mt CO_2eq can be achieved by 2050. This can be greater with sequestration. If 100% of commercial building structures were to be constructed with EWP instead of reinforced concrete, a saving of 13 Mt CO_2eq can be achieved by 2050 when sequestration is considered, a savings of 28 MtCO_2 eq can be achieved. However, it is important to remember that location factors can be of great significance in the outcome of the LCA. Hence, what applies in one jurisdiction may not apply in another. Mass timber products include cross-laminated timber, CLT, glulam, nail-laminated timber, dowel-laminated timber, and massive plywood veneer that are used together with CLT majorly for multi-story buildings [1]. Currently, CLT is the most popular [5]. CLT is well suited for multi-story buildings [6]. In some parts of the world, (e.g., some parts of Africa, China, etc.), concrete buildings are more common. While in other parts, (such as cold climate regions of North America) wooden buildings are common. Although both concrete and mass timber construction has attractive features, wood is regarded as a renewable construction material. Wood is desirable for its reusability and its ability to store carbon for its lifetime [7]. On the other hand, concrete is desirable for its high strength. Among other things, the advantages of concrete include its ability to be formed into different shapes and the ability to harden and gain strength at ambient temperature [8]. In terms of sustainability, while there is concern about resource depletion for 'non-renewable' resources such as limestone for the manufacture of Portland cement (one of the major ingredients in concrete), renewable construction material (such as wood) requires adequate forest management to ensure that adequate forest regeneration practices are in place to support construction works and other uses for wood material without losing all the carbon sequestration privileges that the forest offers.

Given the finite nature of mineral resources, there is a need for diligence to avoid misuse, over-exploitation, and wastage. As a certain resource nears its depletion, a decrease in production is inevitable. A previous work [9] reported that decreased production of some metals (such as lead, silver, and zinc) in Canada resulted from a decrease in proven and probable reserves of those metals. To illustrate the seriousness of resource depletion and the need to ensure adequate forest regeneration, a review of reserves of limestone and forest resources in two locations is considered.

1.1. Resource use: The need for good planning and management of natural resources for construction works

The Amazon basin is described as the largest tropical rainforest in the world, having about 6 - 8 million km^2 of forest house [10].

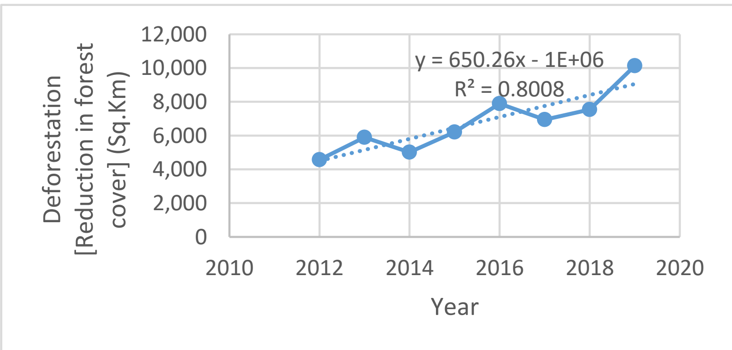

Figure 1. Deforestation in the Amazon rainforest. (*Adapted from Butler, 2020, [11]).

Although wood materials and mass timber are good for construction, if adequate forest management is not practiced to ensure the replanting of trees, there will be a depletion of trees. Benefits that are received from having the forest can also be lost. Figure 1 shows an overview of deforestation in the Amazon rainforest between 2012 and 2019. If good forest management practices are not explored, the forest will be gone eventually. In a similar way, mineral deposits (such as limestone) are also finite. A previous report [12], indicated that a country in Asia has 15 billion metric tons of limestone reserves. Table 1 shows various exploration rates for which this can be depleted. Figure 2 also shows a graphical illustration of how the reserve of the mineral deposits will gradually reduce in a location with various rates of mining. For a 'non-renewable' resource, the number of years to depletion can be obtained by dividing the amount of reserve by the resource extraction rate.

Table 1. Number of years to depletion at varied mining rates for limestone reserve in Country X.

Limestone mining rate (metric tons per year)	Number of years to depletion
250000	60000
500000	30000
1000000	15000
5000000	3000
15000000	1000
150000000	100
1500000000	10
15000000000	1

These data show the need to avoid wastage, recycle as many materials as possible, and explore alternative materials (especially renewable materials) to supplement the use of non-renewable materials in construction operations.

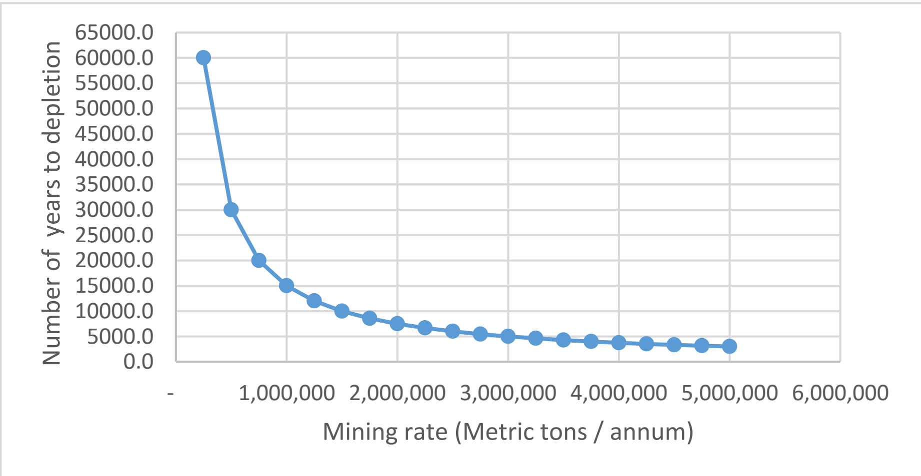

Figure 2. Expected depletion rate for limestone in a country at varying rates of mining.

In addition to resource depletion for a community, other environmental impacts are worth attending to. Life cycle assessment (LCA) methodology gives various environmental impacts that can be associated with construction materials in various stages from product stage to construction, use, and end-of-life stages.

1.2. Life cycle stages of mass timber and concrete structures

A comparison of the lifecycle impact of mass timber and concrete structures requires a deep look into the processes that are involved in the material extraction and processing, construction, the processes that are involved throughout the useful lifespan of the building, and the processes at the end of life of the building. Using the Athena impact estimator for buildings, some scholars [1] did a comparative LCA of a high-rise mass timber building with an equivalent reinforced concrete alternative. The study presented the items in the lifecycle of a building based on EN 15978. This is illustrated in Figure 3.

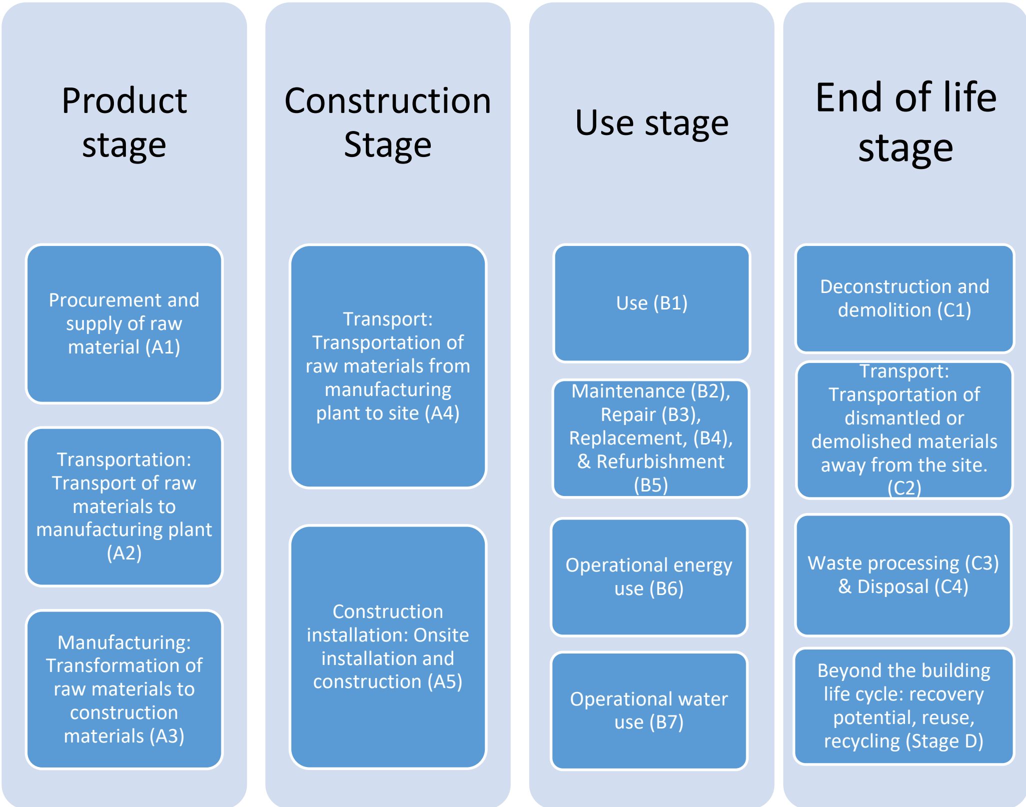

Figure 3. Life cycle stages in a building (Adapted from Chen, Gu, Bergman and Lian, 2020).

1.3. Literature review

Building materials and the associated processes make up a significant part of global emissions [13]. Due to its 'renewability nature' [14, 15] (can be replanted), wood is often favored as a sustainable construction material over the traditional concrete alternative. Low-energy timber building systems with energy-efficient heat supply can help improve the resource efficiency of the built environment [16]. Some scholars [17] reported that when building with timber instead of mineral materials, there is a positive GHG reduction potential. Some other researchers [18] noted that today, the use of wood and engineered wood products is considered an opportunity for the mitigation of negative building impacts such as GHG emissions. As a means of mitigating global climate challenges, globally, timber materials are currently being promoted as construction materials [19]. However, since the environmental impacts of wood are strongly related to forest management, service life, end-of-life scenarios, and waste treatment processes, the sustainability of wood as a construction material is a complex issue [20]. Various researchers have tried to examine the environmental impacts that arise from the use of different construction materials. These impacts vary with location-specific characteristics and local availability of materials. Characterized by unique structural features and better environmental performance, mass timber is considered an alternative to steel and concrete

[21]. By moving wood into building with designs that have traditionally been dominated by concrete and steel, mass timber construction has the potential to reduce greenhouse gas emissions [22]. Using Life cycle assessment LCA, life-cycle cost analysis (LCCA) approach, and the TRACI impact category method, some researchers [23] performed a cradle-to-grave comparison of the environmental and economic performance of a high-rise mass timber building in the Pacific Northwest of the US with a concrete building of similar design for a 60-year life cycle. The scholars reported that the LCA result for the environmental performance of mass timber is better than that of the conventional concrete building. Nevertheless, the total life cycle cost of mass timber building is higher than that of concrete building for a 60-year service life analysis. The uncertainty analysis indicated that a design that allows for the recycling of mass timber and an extension of the lifespan of the building could have a significant reduction in the total life cycle cost of the mass timber building. Some scholars [24] presented a review of 62 peer-reviewed articles relating to mass timber construction as a substitute for conventional construction. Among other things, the scholars reported that the average embodied energy of mass timber buildings is 23% higher than the reinforced concrete alternatives, and the average embodied GHG emissions of reinforced concrete buildings are 42.68% higher than mass timber buildings. The authors noted that the general trend indicates that mass timber buildings have lower global warming potential (GWP) and life cycle primary energy (LCPE) than steel and reinforced concrete buildings. Using three pairs of building designs for the Pacific Northwest, Southeast, and Northeast regions of the United States, (to conform with mass timber building types 8, 12, or 18 stories) A previous work [22] compared the environmental impact of mass timber buildings against functionally equivalent conventional buildings that were constructed with steel and concrete. The scholars reported that when compared with concrete buildings, over all regions, mass timber exhibited a reduction in embodied carbon that varies between 22 to 50%. However, in all mass timber buildings, the total embodied energy during the production, transportation, and construction (A1- A5 materials) was higher than that of the concrete equivalent. The scholars noted that further research is needed to predict the long-term carbon emissions and mitigation potential of mass timber buildings in comparison to conventional building materials.

Some researchers [20] conducted an LCA comparison of a semi-detached house that was made with CLT and a conventional building with equal thermal performance and similar geometric characteristics (made with a reinforced concrete structure and light-clay bricks). The report mentioned that the use of wood resulted in a reduction of about 25% of GHG emissions. The scholars noted that if extended to a large scale, this could help to achieve the community goals of emission reduction in the construction sector. Nevertheless, the scholars reported that during the study, the quantified contributions with purely economic values, the energy that was provided by workers, the energy that was spent on their transport to the workplaces, etc. were not considered. Some other researchers [25] compared the recycling potential of mass timber buildings and that of reinforced concrete buildings. The scholars reported that the disassembly ability and the recycling potential of mass timber buildings are higher than that of reinforced concrete buildings. While the recycling potential for mass timber buildings was 73%, the recycling potential of reinforced concrete was reported as 34% within a 100-year service life. Meanwhile, some other scholars [26] demonstrated the concept of the material passport using a variant in concrete and a variant in timber. The scholars reported that the recycling potential of concrete is better but concrete leads to more waste. In terms of environmental impacts, the authors reported that the timber variant exhibited a significantly lower environmental impact than the concrete variant. On a comparison of a 12-story mixed-use apartment/office building (design for Portland Oregon) that was constructed majorly with some specified quantities of certain mass timber products and a similar concrete building, some researchers [14] noted that although (when compared with similar concrete building) the use of CLT and glulam resulted in consumption of more primary energy, CLT and glulam helped achieve a substantial reduction in the carbon footprint of the building. Using a method that is conceived as a decision-oriented tool that integrates LCA with building information modeling, a previous work [27] reported that according to LCA analysis, wood structures show an overall better environmental performance. Nevertheless, distinctions and contradictory results can be seen in different impact categories. Some scholars [18] quantified the environmental impacts of one of the most common dwelling types in Uruguay. The scholars reported that on a cradle-to-grave assessment basis, for a single-family house in Uruguay, the timber-frame building showed the lowest impact in human toxicity, acidification, global warming potential, freshwater ecotoxicity, and ozone depletion potential. Nevertheless, the timber frame building yielded a higher eutrophication potential when compared with the concrete-masonry-based building. Some researchers [28] evaluated the energy implications of a multi-story residential building over its life cycle for a lifespan of 80 years. The energy and material flows of the life cycle phases of the building versions for the study were designed in accordance with the Swedish building code. Among other things, it was reported that the total life cycle primary energy use of modular and CLT buildings are 9 - 17% and 20 - 37% (respectively) lower than the concrete alternative (when space heating is from combined heat and power).

Some scholars [19] compared the environmental and economic impact of a hybrid floor system (glued-laminated timber, GLT with concrete) and three other floor types (precast reinforced hollow core concrete panel, lightweight steel composite decking, and Cofradal slab composite). The scholars found that GLT-concrete hybrid floor showed lower emissions in all environmental categories such as global warming potential, human toxicity potential, eutrophication potential, terrestrial ecotoxicity, acidification potential, and in fossil depletion potential. GLT-concrete hybrid floor showed a lower embodied energy when compared to all three other floors. However, the GLT-concrete floor has a higher construction cost in some instances. The authors noted that when considering reuse potential at the end of life, GLT-concrete hybrid floors would have a lower total cost. Some researchers [29] performed cradle-to-grave LCA assessments (considering some specified LCA phases) for an 8-story mixed-used building in Vienna (originally built with reinforced concrete). The authors mentioned that it can be shown that the timber building has 47% less total mass than the concrete building. In addition, the timber building showed 18% less embodied carbon while considering stages A1 to A5 (material extraction and processing to end of construction LCA phases) when the whole building life cycle and operational energy use are considered. When comparing stages A1 to A5 with special emphasis on the parameter that describes resource use (PE, primary energy) and global warming potential, mass timber outer performed concrete building in both cases. However, a comparison of results from the US and Australia showed significantly lower differences between the two building types. While the Australian case study only reported 18% lower fossil GWP of mass timber, US partners found 40 to 50% differences. Some researchers, [2], 2016 noted that the use of CLT to replace conventional carbon-intensive material would reduce CO_2 emissions by more than 40% and energy consumption by more than 30% in two cities (one of the cities is referred to as a cold region, and the other is referred to as severe cold regions). Hence, the researchers support the use of CLT in cold regions with proper detailing to minimize environmental impacts. Further research is recommended on the energy use for mass timber as compared to concrete in hot-climate regions (as regards cooling requirements for the buildings). In reference to insulation materials, stone wool has been reported as having lower material production energy when compared to glass wool [16]. Further opportunity to improve resource efficiency for timber-based buildings exists in the choice of insulation.

A previous study [1] reported that for modules A to C, not considering B6 (operational energy use), CLT showed a 20.6% reduction in embodied carbon (when compared with reinforced concrete building), and for modules A to D, not considering B6, the emission from CLT was 70% lower than that of the reinforced concrete building. 1.84 x 10^6 KgCO_2 eq was stored in the wood material for the CLT building during the building's lifetime. The report further mentioned that the greenhouse gas (GHG) emissions of whole buildings can be significantly influenced by the selection of construction materials. Another study [14] found that mass timber performs better than concrete building on environmental impact categories such as global warming, eutrophication, and ozone depletion. However, concrete showed better performance on smog, acidification, and total primary energy demand. Some other scholars [30] replaced steel and concrete building structures with timber structures, then used LCA methods to compare the climate change impact of a reinforced concrete benchmark structure to the climate change impact of an alternative timber structure. For buildings that range from 3 to 21 storeys. It was found that timber structures have a climate change impact that is 34 - 84% lower than reinforced concrete structures. That study focused on selected portions of the LCA process. Some researchers [31] compared the environmental impacts that are associated with alternative designs for a typical North American midrise office building. One design is with laminated timber hybrid design that used engineered wood products (glulam and CLT). The second design is with a traditional cast-in-place reinforced concrete frame. In a cradle-to-construction review, the authors noted that traditional timber buildings showed lower environmental impacts in 10 out of 11 assessment categories.

The selection of low-carbon and sustainable building materials is important in the reduction of the environmental footprint of the built environment [4]. A previous work [32] aimed at investigating challenges that are related to building LCA such as biogenic carbon accounting, (dynamic and prospective aspects) to discuss how they affect LCA results for low-energy buildings and to see what developments are still needed. With a focus on the global warming impact category, three single-family houses that are built with timber frame, cast concrete, and concrete block cavity walls are used as a case study. The scholars reported that timber house was found as the less impacting choice whether it is burned or landfilled (when biogenic carbon is addressed). The cavity wall is the 2nd best while cast concrete was reported as the least favorable in terms of biogenic carbon. The study also indicated that landfilling is considered less impacting for wood than incineration because 97% of wood is considered as permanently sequestered in landfills. If biogenic carbon is not considered, incineration showed a better environmental performance. However, when a dynamic approach and specific prospective scenarios are considered, the gaps between options vary, but the rankings between houses stay the same.

It is widely accepted that the embodied energy of a building may be reduced by the use of timber [2]. Some scholars [33] included embodied carbon as another way of describing the environmental impacts of structural systems. Embodied carbon was defined as the carbon that makes up the material itself as well as the carbon that is emitted from its manufacture. The authors noted that parking garages have little operational energy use, and few materials or systems. Hence, a majority of the environmental impacts during the life cycle are from its embodied carbon and energy. Using a manual material take-off from construction documents of four parking garages with one-way spans, one precast concrete, one post-tensioned concrete, one cellular steel, and one mass timber, the scholars reported that under best material practices, there is little difference in embodied energy for structural systems that are used for parking garages. The report noted that mass timber has marginal gains in embodied carbon and energy performance. This gain was said to be within 30% marginal error in the ICE database. Using the LCA approach, some scholars [34] aimed at exploring the life cycle primary-energy and life cycle greenhouse gas emissions of three high-rise residential buildings in cold regions of China. The three building alternatives considered are CLT, traditional reinforced concrete, and Hybrid CLT. Among other things, the scholars noted that, when compared with the reinforced concrete building over a 50-year life cycle, the CLT and hybrid CLT were found to show 15% and 10.77% lower lifecycle greenhouse gas emissions respectively. In the product and construction stage (when compared with the reinforced concrete building), the CLT and hybrid CLT also showed lower greenhouse gas emissions and primary energy. However, in the operation stage, the reinforced concrete building was found to have lower primary energy and GHG emissions when compared to the CLT alternatives. Some scholars [35] evaluated the LCA of a low-energy residential mass timber building. The scholars reported that the global warming potential of mass timber and reinforced concrete buildings were estimated as 97.4 and 162.8KgCO_2eq per square meter respectively. When compared to conventional reinforced concrete, the researchers reported that over a 50-year useful lifespan, the operational emissions from domestic space conditioning showed a reduction of 83% per square meter. The authors concluded that to reduce the carbon emissions of multi-story buildings in Santiago, Chile, mass timber construction exhibited a higher potential than traditional reinforced concrete. In a study that examined the potential for GHG emission reduction by substituting steel and reinforced concrete multi-story building structures with timber structures.

Some scholars [36] investigated the energy savings and carbon reduction performance of timber stadiums in comparison with stadiums built with reinforced concrete based on life cycle carbon assessment and life cycle energy assessment. The simulation environment considered five cities in five climatic zones in China. the scholars reported that the Life cycle energy assessment results show that the energy saving potential of timber stadiums is 11.05%, 12.14%, 8.15%, 4.61%, and 4.62% lower than those of reinforced concrete buildings in 'severely cold', 'cold', 'hot summer-cold winter', 'hot summer-warm winter', and temperate regions respectively. The carbon emissions of timber stadiums are 15.85%, 15.86%, 18.88% 19.22% and 22.47% lower in the regions mentioned. The scholars also reported that simulation results indicate that in all climate regions, timber is a more sustainable building material. However, the carbon reduction potential and energy savings are greatest in cold regions. The authors noted that as a building material, in regions without considerable space heating during the winter, timber lacks effectiveness. The scholars mentioned that the carbon reduction effects of timber during the operation stage are less notable in hot-summer, warm-winter, and temperate regions. This also calls for more study on how mass timber behaves in reference to other construction materials, especially in warm and hot climate regions. Further research is also recommended on the impact of various forms of insulation on the thermal performance of mass timber.

To confirm the specific advantages of timber buildings, lots of LCA studies from various international stakeholders have compared conventional buildings with timber buildings. However, the difference in approach, database, system boundaries, and scope makes it impossible to compare these studies [17]. The scholars highlighted the importance of conducting comparative LCA of buildings in accordance with widely accepted system boundaries and consistent databases to avoid double counting of advantages due to carbon storage. Some researchers [37] noted that aside from comparing beam-floor systems based on weight, speed of installation, cost, etc., a comparison can also be based on their environmental impacts. The scholars also mentioned that for the beam-floor system, depending on the quantity of recycled steel, there are opportunities for improvement in the environmental impacts as the ratio of virgin-recycled steel in a beam-floor system can show a wide variation of the impacts on the environment. The report mentioned that due to the large impact on agricultural land occupation of spine and spruce in the production of glulam, glulam beams have a noticeably higher impact on the ecosystem than reinforced concrete and steel beams. The report further stated that in the assessment for Europe, the impact on ecosystems appears to be a lot more important than the assessment method for the rest of the world. The conflicting reports that are sometimes seen in the comparison of the environmental impact of concrete and timber products call for further studies on the environmental impacts of various construction materials while considering location-specific parameters. Although it may be difficult to compare LCA studies with different approaches, databases, system boundaries, and scopes, it is important to continue studies on LCA for various municipalities to know what material selection will be the most environmentally friendly considering local conditions. Some scholars [21] used the LCA approach for a comparative analysis of a baseline concrete building and a functionally equivalent timber building that has cross-laminated timber, CLT as the primary material. The scholars reported that mass timber building has a 25% reduction in global warming potential compared to its concrete counterpart. However, in a number of impact categories (such as acidification potential of soil and water sources AP, formation potential for tropospheric ozone, SFP, etc.), the concrete building performed better. The system boundary for this construction is cradle-to-gate (material extraction and processing to the end of construction). The authors noted that this could be associated with a longer transportation distance for CLT material. The scholars further reported that through local sourcing, manufacturing optimizations, and enhanced logistics, the environmental performance of timber buildings could be further improved. The two buildings that were evaluated are both eight-story residential. The scholars recommended further studies of various types of buildings in different geographical locations. LCA has been widely used to evaluate the environmental impact of mass timber construction as a substitute for conventional construction [24]. This study applied LCA in the comparative analysis of life cycle impacts of mass timber and building construction using a design for Calgary, Alberta.

2. Materials and Methods

In addition to a literature review on the life cycle analysis of mass timber and concrete construction, generic building drawings were made using virtual architect software (for illustrative purposes). Athena's impact estimator for buildings 5.4 was used to design and evaluate the life cycle impact of a building (with a floor area of 119.88m^2) from cradle to grave. The life cycle impacts of selected mass timber (glulam, cross-laminated timber, CLT, laminated veneer lumber / Parallel-strand lumber, LVL/PSL) were compared with that of concrete blocks. Some of the results of this analysis were compared with some previous works in this area. Although the material selection for the LCA includes the foundations, floors, walls, columns, beams, and roofs for the project, for this report, the material properties of walls, columns, and beams were varied in 3 categories as shown in Table 2. The foundation, floor, and roof were designed with the same material. The design presented is for an illustrative purpose for research only. Figure 4 is a figurative illustration of different wall types.

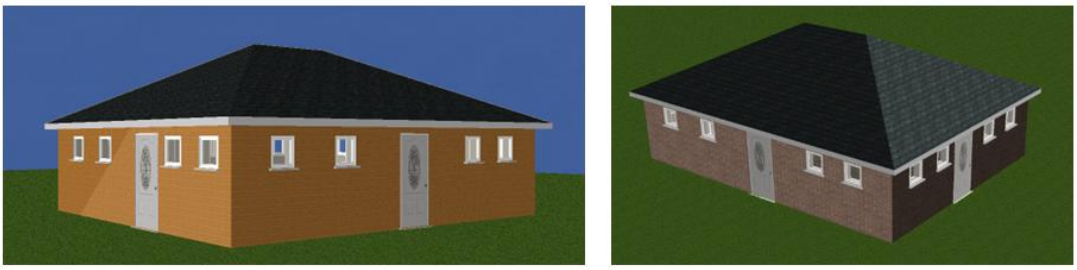

Figure 4. Generic buildings for LCA analysis (illustrative purpose only for two different wall types)

2.1. The software

Athena impact estimator for buildings is an LCA-based software package that helps designers to easily include environmental information while still in the early stages of a project. Users can describe building assemblies through dialogue boxes. Bill of quantities can also be imported from any CAD program. [38]. Result from Athena impact estimator for buildings software covers phases (A1 to A5, B2, B4 and B6, C1 to C4, and D).

Table 2. Variation of material properties for experimental design.

Building elements	Material group 1	Material group 2	Material group 3
Columns	Concrete	Glulam	LVL / PSL
Beams	Concrete	Glulam	LVL / PSL
Walls	Concrete blocks- Envelope category: concrete bricks (Cladding)	Cross laminated timber, CLT- Envelope category: Spruce wood bevel siding (Cladding)	Cross laminated timber, CLT- Envelope category: Spruce wood bevel siding (Cladding)

Other materials included in material groups 1, 2, and 3 are included in Table 3.

3. Life Cycle Analysis

LCA is one of the techniques that is being developed to better understand and address environmental protection and possible impacts that are associated with products. The four phases of an LCA study include goal and scope definition, inventory analysis, impact assessment, and interpretation. The goal and scope show the reason for the study and the processes that are covered in the LCA. System boundary shows which processes will be included in the LCA. Life cycle inventory includes the process of collecting data that are needed to meet the goals of the study (i.e. an inventory of input/output data for the study). The life cycle impact assessment phase (LCIA phase) is a stage in which additional information that is needed to analyze the results from the life cycle inventory is provided [39]. The interpretation stage gives an explanation of the results.

3.1. Goal and scope definition

The goal of this analysis is to compare the result of LCA of construction material such as concrete and mass timber using Athena's impact estimator for buildings 5.4 with previous works. A previous study [1] compared the LCA report for a 12-storey building having end of building life treatment in 60-years. The selected system boundary was cradle to grave. This includes the product stage (A1 to A3), construction process stage (A4 and A5), use phase (B2, and B4), end of life stage C1 to C4) and beyond building life stage D. For the design in the present study, information on the operational energy use is not available. Hence, this phase was excluded from the report. Also, information on the transport phase beyond the building life stage is not available. This is excluded from the report too. Results from Athena impact estimator for buildings also does not include operational water use (phase B7 in Figure 3).

3.2. Life cycle inventory

As mentioned above, life cycle inventory includes the process of collecting data that are needed to meet the goals of the study. The input material quantities that were varied in the study is described in the project methodology. Table 3 shows the bill of quantities for materials types 1, 2 and 3. Material type 1 comprises concrete beams and columns, with walls having concrete blocks, concrete bricks as envelope material (cladding). Material type 2 comprises Glulam beams glulam columns, CLT walls with spruce wood bevel siding as envelope material (cladding). Material type 3 comprises LVL / PSL columns and beams, CLT walls with spruce wood bevel siding as envelope material (cladding). Information input to the software also includes location under evaluation (Calgary), life expectancy (60 years), building type (single family residential), Floor area

(119.88 m²) and building height (4.5m). Material choice assembly input includes foundations, beams and columns, floor, walls, and roof. The design for this evaluation gave a unified selection for the foundation type and material (Slab on grade with brown cellulose insulation in the envelope category). The floors were designed as 9 bays with a bay size of 4m and span of 3.3m with a concrete hollow core envelope. The roofs were designed as a light frame wood truss (pitched), with 12mm thick plywood decking. Little extra allowance was provided for the roof and foundation area. The input for the roof dimensions in Athena software is 10m span x 13m width. The input for the foundation dimension in Athena is 12m x 14m. If a lighter structure is desired for various technical reasons, the structures with more wood components will be preferred.

Table 3. Material groups 1, 2 & 3 for the LCA for the three building scenario.

Material	Unit	Material group 1	Material group 2	Material group 3
#15 Organic Felt	m^2	889.23	889.23	889.23
8" Normal Weight Concrete Block	Blocks	2100.83	-	-
Aluminum Window Frame	kg	76.55	76.55	76.55
Ballast (aggregate stone)	kg	7445.45	7445.45	7445.45
Blown Cellulose	m^2 (25mm)	311.63	311.63	311.63
Cold Rolled Sheet	Tonnes	0.03	-	-
Concrete Benchmark CAN 25 MPa	m^3	6.27	6.27	6.27
Concrete Benchmark CAN 30 MPa	m^3	61.34	35.26	35.26
Cross Laminated Timber	m^3	-	14.39	14.39
Concrete Brick	m^2	168.07	-	-
Expanded Polystyrene	m^2 (25mm)	24.89	24.89	24.89
Galvanized Sheet	Tonnes	0.22	0.22	0.22
Glass Fibre	kg	315.00	315.00	315.00
Glazing Panel	Tonnes	0.36	0.36	0.36
GluLam Sections	m^3	-	6.97	-
Grout-Coarse	m^3	6.73	-	-
Hollow Structural Steel	Tonnes	-	0.16	0.16
Laminated Veneer Lumber	m^3	0.33	0.33	6.68
Mortar	m^3	6.78	-	-
Nails	Tonnes	0.12	0.12	0.12
Precast Concrete	m^3	11.21	11.21	11.21
Rebar, Rod, Light Sections	Tonnes	5.80	0.41	0.41
Roofing Asphalt	kg	4997.69	4997.69	4997.69
Screws Nuts & Bolts	Tonnes	-	0.02	0.02
Small Dimension Softwood Lumber, kiln-dried	m^3	4.05	4.05	4.05
Softwood Plywood	m^2 (9mm)	172.42	172.42	172.42
Solvent Based Alkyd Paint	L	2.72	2.72	2.72
Spruce Wood Bevel Siding	m^2	-	422.57	422.57
Type III Glass Felt	m^2	1778.46	1778.46	1778.46
Water Based Latex Paint	L	-	227.26	227.26
Welded Wire Mesh / Ladder Wire	Tonnes	0.34	0.34	0.34
Total mass value	Tonnes	312.26	150.45	155.08

Quantification of the impact of building materials can be important in developing an effective greenhouse gas mitigation strategy [1]. An advantage of quantifying environmental impacts whilst comparing different building materials like that shown in

Table 3 is that it can help the manufacturers to know how their products compare with other products. This can lead to further evaluation of opportunities for improvement. Lessons learned from LCA results can also help builders in the selection of construction processes. Lifecycle studies show that the production stage of a low-energy building may contribute to a significant portion of the total lifecycle primary energy use and this depend on the location of the building, energy supply system and lifespan, climate, and methodological choices [16]. For example, a previous study [14] reported that lowering the amount of gypsum and moving production close to the site is a potential way to lower the environmental footprint of mass timber building. Another study mentioned that [40] mentioned that for wood construction, the influence of ancillary materials is highest as a lot of screw nails and other connectors are important. The choice of insulating materials was found to have a significant impact on the production primary energy use of the buildings [16].

3.3. Life cycle impact assessment

The environmental impact categories that were identified in this study includes global warming potential, human health (HH particulate), acidification potential, eutrophication potential, ozone depletion potential, and smog potential. Other previous works has also identified various environmental impacts in their LCA analysis. Very little studies incorporate all the stages of a full LCA (Cradle-to-Cradle) [37]. Table 4 shows a list of some previous LCA related studies with system boundaries and environmental impacts.

Table 4. Some previous works showing system boundaries and environmental impacts.

Reference number	Year of publication	System boundary	Environmental Impacts that were evaluated
[1]	2020	Cradle to grave	Global warming potential, human health (HH particulate), acidification potential, Eutrophication potential, Ozone depletion potential, and Smog potential
[14]	2020	(Except B6: operational use phase)	Global warming, ozone depletion, smog, acidification, eutrophication, total primary energy, non-renewable fossil, non-renewable nuclear and renewable.
[13]	2020	Cradle to gate (site) A1 - A5	Embodied emission (Global warming potential).
[33]	2019	Modules A1 - A3 production of building materials, cradle to gate), A4 (transportation of building materials to the building site), and B4 (replacement of building materials through the building lifetime/study period).	Embodied carbon; embodied energy.
[37]	2018	Cradle to gate: extraction of resources, transportation, manufacturing and fabrication of construction materials.	Human health, ecosystems, resources, ozone depletion, climate change, human toxicity, agricultural land occupation, and photochemical oxidant formation.
[17]	2017	Cradle to Grave	Global warming potential (fossil and biogenic).
[30]	2016	Modules A1 - A3 (product stage), B2 (Maintenance), B4	climate change impact

		(Replacement), C3 (Waste processing), C4 (Disposal) D(Benefits and loads beyond system boundary)	
[32]	2015	Cradle to gate	Global warming impact.
[18]	2020	A1 - A5. Cradle to Building construction, B5, B6, C1 - C4	Global warming potential, human toxicity acidification potential, ozone depletion potential and fresh water aquatic ecotoxicity, but it showed the highest impact in Eutrophication potential.
[3]	2018	A1 raw material supply, A2 transport of material to factory, A3 manufacturing, A4 transport to the construction site, A5 construction process, B2 maintenance, B3 repair, B4 replacement of building materials and components, B6 operational energy use, C1 deconstruction, C2, transport to final disposal, C4 final disposal	Global warming potential (measured in CO2 eq)
[4]	2016	(B7 operational water use was excluded).	Global warming potential, human health (HH particulate), acidification potential, Eutrophication potential, Ozone depletion potential, and Smog potential
[2]	2016	Cradle to grave: global warming potential	Global warming, ozone depletion, smog, acidification, eutrophication, total primary energy, non-renewable fossil, non-renewable nuclear and renewable.
[16]	2014	Production, operation and end-of-life phases	Embodied emission (Global warming potential).
[31]	2012	A1 - A3 (product stage), A4 - A5 (Construction process stage), B1 - B7 (Use stage), C1 - C4 (End of life), D1 - D4 (Benefits and loads beyond the system boundary)	Embodied carbon; embodied energy.
[40]	2009	Cradle to gate	Human health, ecosystems, resources, ozone depletion, climate change, human toxicity, agricultural land occupation, and photochemical oxidant formation.

4. Results

Table 5 showed a result of comparison of environmental impacts for certain mass timber and concrete components. Material groups 1, 2 and 3 are earlier described. Table 5 indicated that for the material selection for this location, material group 1 (building with more concrete material in the material design) showed over 200% more global warming potential than materials group 2 and 3 (having more mass timber material). In fact, the impacts from material group 1 are consistently higher for all the LCA measures that are evaluated for this location. Note that this building was designed for Calgary, Alberta. The result may be different for other locations, depending on various local conditions.

Table 5. Comparison of life cycle impacts between different material groups – Results from Athena impact estimator for buildings (Phases A to D of LCA, excluding operational energy use).

LCA Measures	Material group 1	Material group 2	Material group 3	Material group 1 vs. group 2	Material group 1 vs. group 3	Material group 2 vs. group 3
Global Warming Potential, kg CO2 eq	5.54E+04	1.62E+04	1.83E+04	242%	202%	13%
Acidification Potential, kg SO2 eq	3.31E+02	2.06E+02	2.15E+02	60%	54%	4%
HH Particulate, kg PM2.5 eq	1.00E+02	6.22E+01	6.27E+01	61%	60%	1%
Eutrophication Potential, kg N eq	2.42E+01	1.58E+01	1.62E+01	53%	50%	2%
Ozone Depletion Potential, kg CFC-11 eq	3.96E-04	2.37E-04	2.17E-04	67%	82%	-8%
Smog Potential, kg O3 eq	6.38E+03	4.17E+03	4.27E+03	53%	49%	2%
Total Primary Energy, MJ	9.09E+05	6.87E+05	7.07E+05	32%	29%	3%
Non-Renewable Energy, MJ	8.75E+05	6.17E+05	6.31E+05	42%	39%	2%
Fossil Fuel Consumption, MJ	8.12E+05	5.89E+05	6.02E+05	38%	35%	2%

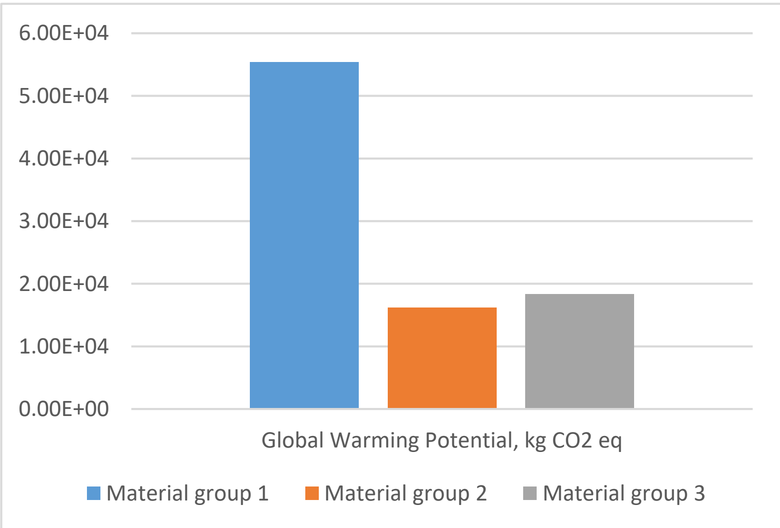

Figure 5. Comparison of global warming potential for varied material groups

Figure 5 indicated that material group 1 with more concrete based component showed more global warming potential for the area being evaluated than material groups 2 and 3 with more wood component in the building design.

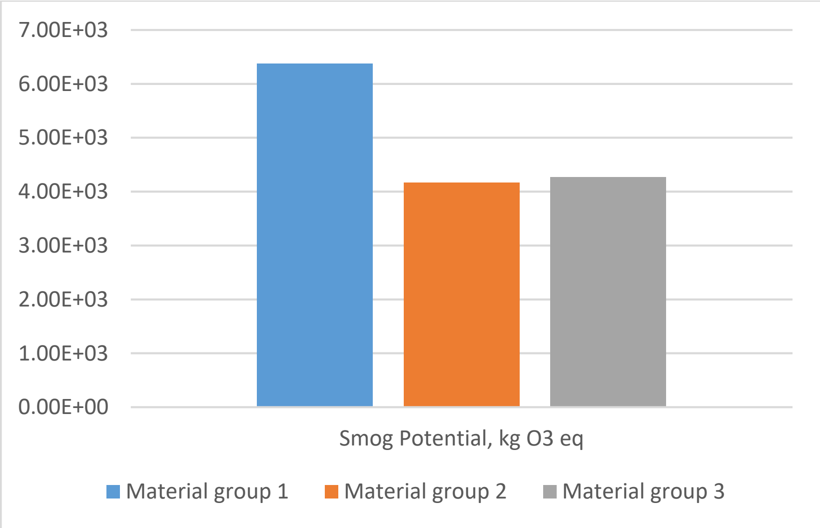

Figure 6. Comparison of smog potential for varied material groups

Figure 6 showed that the material group 1 with more concrete based material has higher smog potentials than material group 2 and 3. While material groups with higher content of LVL/PSL material showed a slightly higher impact in smog potential than material group 2, this difference is not as pronounced as that between material groups with higher concrete-based material. As also shown in Table 5.

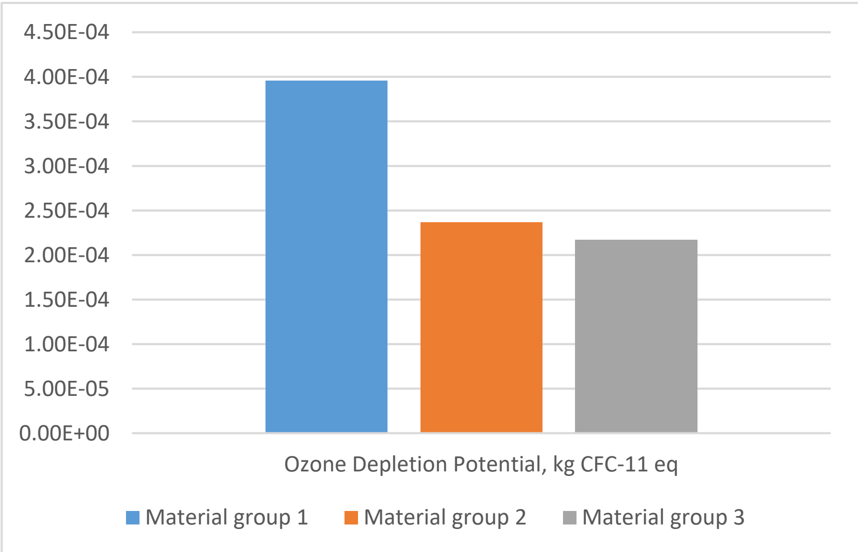

Figure 7. Comparison of ozone depletion potential for varied material groups

Figure 7 showed that the material group 1 with more concrete based material has higher ozone depletion potential than material group 2 and 3. While material group with higher content of LVL/PSL material showed a slightly lower impact in smog potential than material group 2 (with glulam beams and columns), this difference is also not as pronounced as that between material groups with higher concrete-based material.

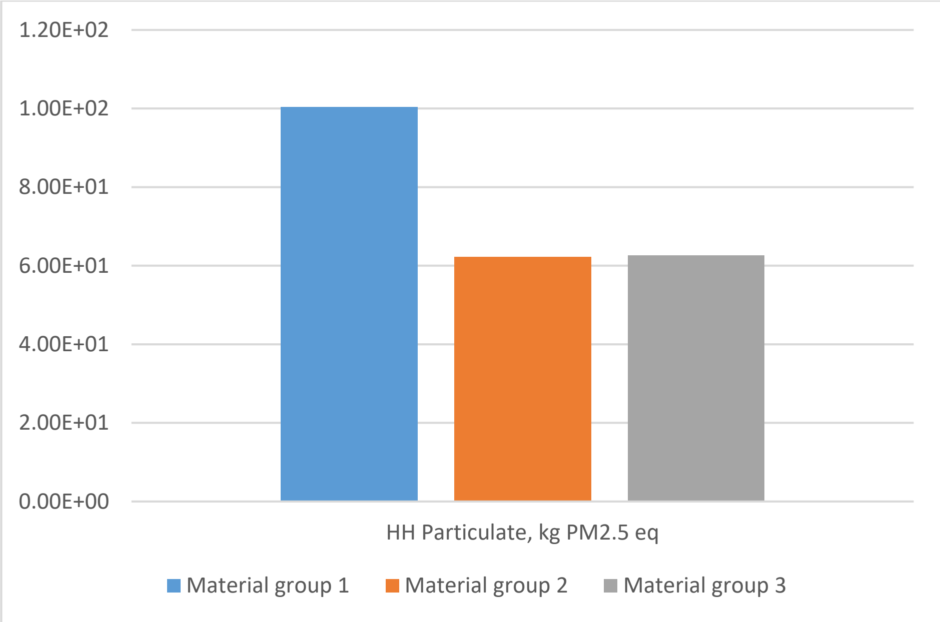

Figure 8. Comparison of human health particulate for varied material groups as measured by PM2.5 eq

Building with concrete bricks also showed a higher impact on the human health category as measured by the amount of PM2.5 for the location that is being reviewed. Table 5 above and Figure 8 showed that the building with brick walls has 61% higher rate of HH potential than the building with glulam beams and columns with CLT walls and spruce wood bevel siding as envelope (cladding). When the building with brick walls is compared with the building with LVL/PSL columns and beams and CLT Walls (group 3), the building with brick walls showed a higher HH potential 60% than the building with LVL / PSL columns and beams with CLT walls and spruce wood bevel siding as envelope. The material design with LVL/PSL component has a slightly higher HH potential than the building whose material was designed to have Glulam columns.

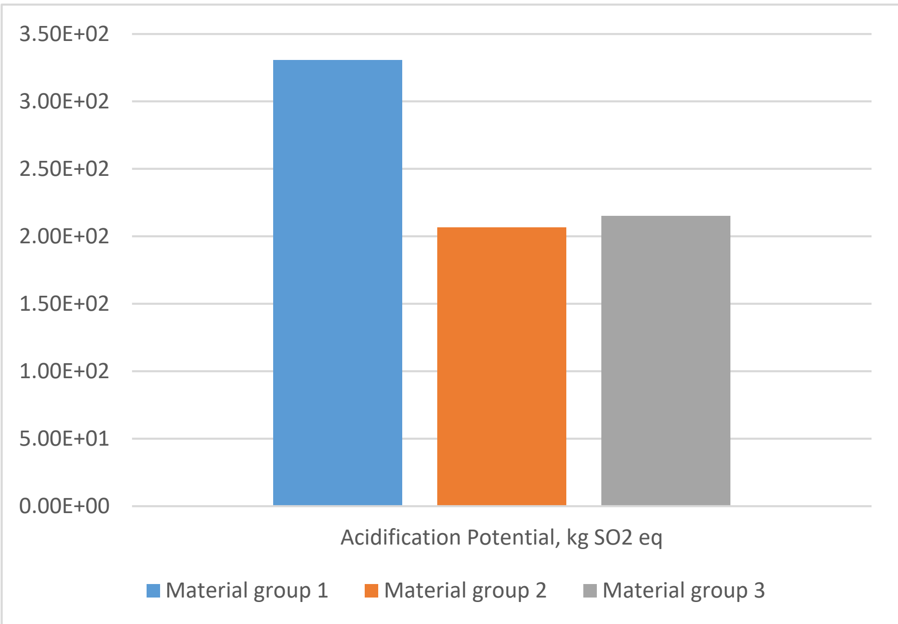

Figure 9. Comparison of acidification potential for varied material groups

The building design with more concrete-based material also showed a higher acidification potential for the location that is being reviewed (as shown in Figure 9). Table 5 above showed that the building with brick walls has 60% higher rate of acidification potential than the building with glulam beams and columns and CLT walls with spruce wood bevel siding spruce as envelope. When the building with brick walls is compared with the building with LVL/PSL columns and beams and CLT Walls, the building with brick walls showed a higher acidification potential that is 54% higher than the material design with LVL / PSL columns and beams with CLT walls and spruce wood bevel siding as envelope (cladding). The building with LVL/PSL beams and columns has a slightly higher acidification potential than the building whose material was designed to have Glulam beams and columns.

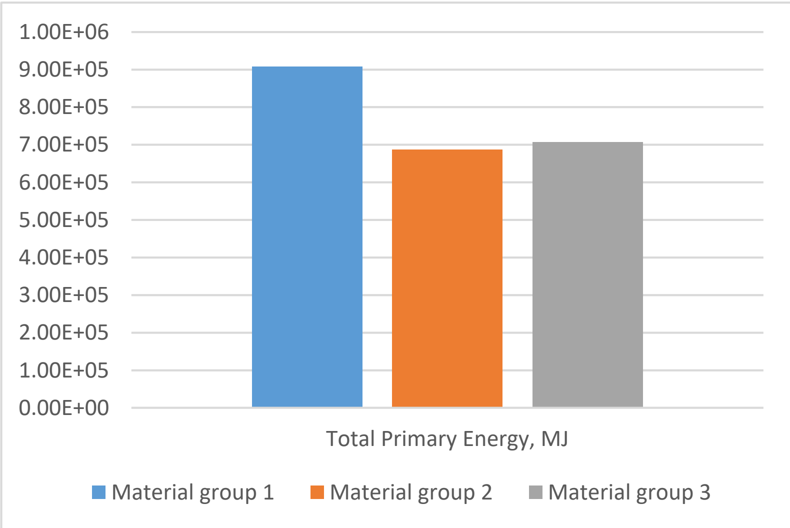

Figure 10. Comparison of total primary energy for varied material groups

Table 5 and Figure 100 also showed that material group 1 has higher total primary energy consumption than material groups 2 and 3.

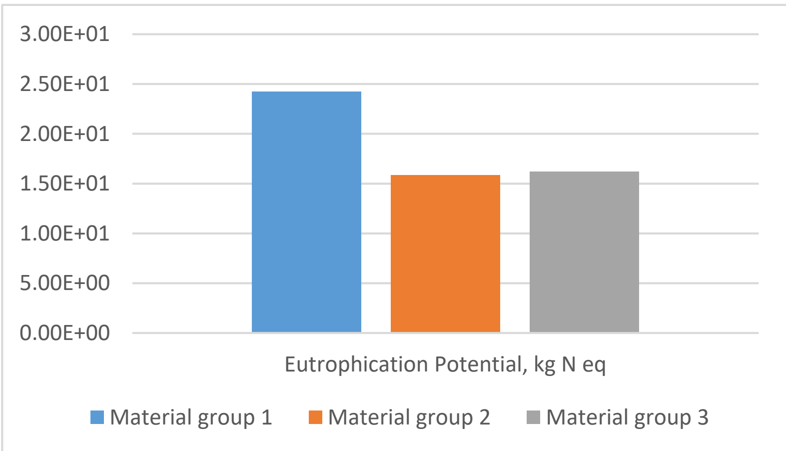

Figure 11. Comparison of impact on eutrophication potential (Kg N eq)

Building with more concrete-based material (group 1) also showed a higher impact on the eutrophication potential category for the location that is being reviewed. Table 5 and Figure 111 above showed that the building with more concrete-based materials has 53% higher rate of eutrophication potential than the building with glulam beams and columns, CLT walls (Material group 2). When the building with more concrete-based material is compared with the building with LVL/PSL columns and beams, and CLT walls (Material group 3), the building with more concrete-based materials showed a higher HH potential 50% than the building with LVL / PSL columns and beams, CLT walls and spruce wood bevel siding as envelope (cladding). The material design with LVL/PSL component has a slightly higher eutrophication potential than the building whose material was designed to have glulam columns and beams.

4.1. Narrowing the analysis down to smaller building sections

Tables 6 and 7 showed that the specified LCA measures are higher for the material combination with higher concrete components (group 1) than those with higher wood components. Table 6 showed the LCA result for the column and beam sections only. Table 7 showed the LCA result for the wall sections. Results in Table 6 also showed that concrete beams and columns have higher environmental impacts than the wood-based components.

Table 6. Combined LCA results for stages A to D (not including the operational energy use phase) for beams and columns sections of the design – from Athena impact estimator for buildings.

LCA Measures	Columns and beams, (Concrete)	Columns and beams, (Glulam)	Columns and beams (LVL/PSL)
Global Warming Potential, kg CO_2 eq	1.63E+04	-1.75E+03	3.97E+02
Acidification Potential, kg SO_2 eq	7.68E+01	1.17E+01	2.03E+01
HH Particulate, kg PM2.5 eq	3.10E+01	1.81E+00	2.30E+00
Eutrophication Potential, kg N eq	5.43E+00	1.23E+00	1.57E+00
Ozone Depletion Potential, kg CFC-11 eq	8.68E-05	2.42E-05	4.26E-06
Smog Potential, kg O_3 eq	1.41E+03	2.15E+02	3.13E+02
Total Primary Energy, MJ	1.82E+05	2.91E+04	4.87E+04
Non-Renewable Energy, MJ	1.76E+05	1.69E+04	3.04E+04
Fossil Fuel Consumption, MJ	1.44E+05	1.69E+04	3.04E+04

Narrowing the present analysis to the wall section, Table 7 indicated that life cycle impacts for concrete-based walls are higher than the wood-based counterparts

Table 7. Combined LCA results for stages A to D (not including the operational energy use phase) for wall sections of the design.

LCA Measures	Concrete walls, concrete brick-cladding	Cross laminated timber walls, Spruce wood bevel siding-cladding
Global Warming Potential, kg CO_2 eq	1.42E+04	-6.91E+03
Acidification Potential, kg SO_2 eq	9.15E+01	3.25E+01
HH Particulate, kg PM2.5 eq	3.08E+01	2.18E+01
Eutrophication Potential, kg N eq	6.16E+00	1.96E+00
Ozone Depletion Potential, kg CFC-11 eq	1.05E-04	8.68E-06
Smog Potential, kg O_3 eq	1.77E+03	7.64E+02
Total Primary Energy, MJ	1.61E+05	9.28E+04
Non-Renewable Energy, MJ	1.53E+05	5.38E+04
Fossil Fuel Consumption, MJ	1.42E+05	4.58E+04

4.2. Comparison of total mass of the buildings with varied material components

In a comparison of the LCA for a 12-storey building (with floor area of 8360m^2) that is constructed with CLT and a functional equivalent that is a reinforced concrete building (using Athena Impact estimator for buildings, IE4B) [1], it was reported that the total mass of the CLT building was 33.2% less than that of reinforced concrete building. In the present analysis, with floor area of 119.88m^2, the building whose material specification was designed to have more concrete-based materials will be about 101% heavier than the building whose material specification is designed to have Glulam Beams and Columns; CLT walls with Wood bevel siding spruce as envelope. The difference between the total mass value of materials group 2 and 3 is very little. Although the building scale is different, the result of the present analysis also confirmed the fact that replacing certain concrete components of the building with mass timber can help achieve a reduced weight. An expanded bill of quantities including the total mass value for these three designs is included in the appendix section of this article.

5. Discussion

Results from this study are in line with the majority of previous works. Some scholars [31] compared environmental impacts that are associated with a traditional cast-in-place reinforced concrete frame and a laminated timber hybrid design for a 14,233m^2 North American mid-rise office building (in Burnaby, BC). The laminated hybrid design utilizes CLT and glulam. Using TRACI characterization methodology to translate inventory flows into impact indicators, with a system boundary from cradle to construction (for the structural support system and the building envelope), for a 50-year building horizon, the result showed that laminated timber building exhibited lower environmental impacts in 9 out of 10 assessment categories. Apart from fossil fuel depletion in which the concrete-framed design category showed better performance, laminated timber frame design exhibits better performance on global warming potential, ozone depletion, human health effects, criteria air pollutants, water intake, eutrophication, ecological toxicity, smog, and acidification. It was reported that the timber building demonstrated a much higher cradle-to-gate embodied energy. The authors also noted that the result was not in line with previous works. However, it was reported that none of the previous works has looked into the exact scenario that the authors described. This contradiction also showed the need for a continuous evaluation of the LCA of construction works for different building specifications. Some other scholars [18] reported that a cradle-to-grave assessment of timber-frame building produced the lowest impacts on global warming potential, human toxicity, acidification potential, ozone depletion potential, and freshwater aquatic ecotoxicity, but it showed the highest impact in eutrophication potential. Another study [17] calculated substitution factors based on the LCA calculations of different constructions (timber and mineral). It was noted that there is a positive GHG reduction potential when building with timber instead of using mineral materials. In the present study (as illustrated in the result section), the design with mass timber components in the beams, columns, and walls exhibited better environmental performance than the design with concrete-based material. This present study also shows a much higher difference in GHG emissions for the building design with more concrete-based materials (in phases A to D of LCA) than other material groups in the study.

Although the analysis for this study showed that wood is more environmentally friendly than concrete for certain sections of the building, there are opportunities for improvement of the environmental footprint of concrete. Previous studies have reported that good use has been found for certain GHG emissions. CO_2 has found uses in cement works. Some researchers [41] reported that CO_2 upcycling can improve the compressive strength of cement paste by 5.8 - 9.9% at the ages of 3 - 56 days. The initial and final setting times is also reduced. The scholars [41] reported that the introduction of CO_2 in the form of Nano-$CaCO_3$ refined the pore structure and accelerated the early age hydration of Portland cement. Some other scholars [42] reported that the introduction of CO_2 into concrete did not compromise the expected durability performance of treated concrete, rather it helped reduce initial set time by up to 40%, and increase one and three-day compressive strength by 14 and 10% respectively. These developments showed prospects for some reduction of environmental impacts not only for concrete but also for the entire construction operations. Section 1.1 illustrated a scenario of how both wood and limestone reserves can be depleted eventually if proper planning and good resource management principles are not employed. Although concrete may not be as environmentally friendly as wood, for some sections of the building construction, concrete is still a good substitute for wood. Concrete is preferable to wood for certain construction where water/moisture may be an issue. Although a multitude of benefits has been proven to come with the use of timber products in the construction sector, under certain conditions, such as potentially unfavorable environmental conditions, and designers' inexperience, there are major concerns about early degradation of structures and components, unhealthy conditions of the indoor environment and occupant's discomfort [43]. Some scholars [43] used hygrothermal simulation to evaluate the risk of failure of timber-framed and mass timber emerging external wall assemblies in major Australian cities. The sensitivity of simulation outcomes with respect to indoor climate input data was also evaluated. Hygrothermal performance such as condensation and mold growth risk were considered. Mass timber envelope was found to perform better than timber-framed envelope in different scenarios but with changes in the indoor climate model variation, the hygrothermal behavior of the massive envelope solution changes. The study highlighted the need to address condensation risk and moisture safety in timber envelopes from the early design stage. Specifically, among other things, the report indicated that with respect to heat transfer and moisture management, an underperformance was recorded for timber-framed selected wall assemblies. The authors recognized the limitation of simulations and recommended further studies for a better understanding of the hygrothermal behavior whilst evaluating design alternatives in terms of the configuration of layers and material selection.

In addition, it takes a considerable length of time for trees to reach maturity. Hence, in resource management for construction operations, depending on the local availability of materials and holistic lifecycle assessment of the environmental impact that is associated with the transportation of wood products from long distances, the use of concrete materials may be the most feasible option. As regards the building process, some scholars [40] reported that the longer the transport distances, and the heavier the materials that are used, the bigger the influence of transports on LCA results. The differences in the environmental impacts of different mass timber products show that there are opportunities for improvement. Material manufacturers can compare the environmental impacts of their products with other products to evaluate how they can reduce the environmental impacts in their manufacturing processes.

5.1. Implication of the weight of certain building components on chances of survival in earthquake-prone regions

Evaluation of the results also showed that the concrete beams and columns have significantly higher mass than the other wood-based products. For earthquake-prone regions, if the columns and beams happen to collapse on any resident during a severe earthquake, there will be a heavier impact from a design with more concrete-based materials than with the wooden materials presented. A similar effect may be noticed if this is a multi-story building with concrete floors. If there is no fire during the earthquake and subsequent col-lapse of buildings occurs, given the chance of lesser impact from heavy components of the building, a higher chance of survival is expected for occupants of wooden buildings (in earthquake-prone regions) than occupants of concrete-based buildings. A consideration of the weight of certain building components that can collapse on building occupants is important in LCA for earthquake-prone regions because, in addition to potential fatalities and property loss, earthquakes can reduce the expected lifespan of a building (depending on the severity). This reduction in building lifespan will shorten the time to reach stages C and D of LCA presented in Figure 3 of this report.

Overall, this study showed that when compared with concrete, engineered wood products showed a better environmental performance for the structure and for the location that was evaluated. Nevertheless, another study [44] showed that traditional lumber exhibited better environmental performance than certain engineered wood products in the design of some sections of a building. This may be due to extra energy and resources that are used in the processing of engineered wood products. Further study is recommended on the evaluation of construction processes where traditional lumber or engineered wood lumber will be a preferable choice. In addition to the environmental impacts of construction works, other factors for consideration in sustainable construction also include cost, technical and social factors. Further research is recommended on the incorporation of social, economic, and other technical factors for the evaluation of material selection for various building components in different jurisdictions. Furthermore, LCA results will change as the world sees improvements in capturing and management of emissions in material production and construction processes. Continuous LCA analysis of processes in the whole-building life cycle is recommended to evaluate opportunities for continuous improvement of environmental impacts at different times. Further research on the evaluation of the environmental impacts of various construction materials from a system dynamic point of view (considering location-specific parameters) is also recommended. In construction operations, it is important to ensure that material selection for various parts of the construction is one that gives the minimum impact from a holistic viewpoint.

6. Conclusions and Recommendations

This study presents a literature review on the use of mass timber and concrete in building construction. To further gain insights into the environmental impacts, using Athena impact estimator for buildings, this study compared the results of an LCA study for a single-family house with concrete beams, columns and walls with brick in the envelope category, with those that are made with glulam beams, glulam columns, CLT walls with spruce wood bevel siding in the envelope category and another building with LVL / PSL columns and beams, CLT walls with spruce wood bevel siding in the envelope category. The results are in line with those that were reported by the majority of previous researchers. For the location that was reviewed (Calgary, Alberta) in this study, the design with more wood-based materials having mass timber components showed better environmental performance than those with more concrete-based materials. For the material design for this report, for the chosen location, buildings with more concrete-based materials showed more than 200% and 50% higher global warming and acidification potential respectively than the building design with more wood-based materials. The difference of global warming and acidification potential for buildings with LVL/PSL and those with Glulam component is not as pronounced as when compared with the building design with more concrete-based material. Further results breakdown is presented in the report. This report further shows that LCA can be helpful during the preliminary design to evaluate the expected environmental impacts from the choice of different materials. Lessons learned from LCA results can help builders in selection of more environmentally friendly materials and construction processes in various jurisdictions. For example, some scholars [16] noted that lowering the amount of gypsum and moving production close to the site is a potential way to lower the environmental footprint of mass timber building. Although construction with wood products showed better environmental performance for the location that was reviewed in this report, resource availability and resource depletion potential is an important factor to consider in LCA evaluation and decision on choice of construction materials. Analysis of resource depletion for both limestone reserve in a municipality as well as forest reserve in another jurisdiction showed that both resources can be depleted sooner than expected if adequate resource management strategy is not employed. As regards forest reserves, there is a need for sustainable forest management to be able to use wood for construction in a sustainable manner. In earthquake-prone regions, given that collapse of buildings during severe earthquakes can result in physical injuries, loss of life and reduction in the expected lifespan of the building, in LCA analysis, it is important to give consideration to all aspects of the building materials and material selection that can cause adverse impacts to humans in these areas. Athena impact estimator for buildings has capabilities to show the total mass value of the input information during the building design. Building structural components with lighter components (such as wood-based products) in earthquake-prone regions can result in lesser chance of impacts from heavier building components. This is expected to result in a higher chance of survival (if the building is not engulfed with fire). Nevertheless, while both wood-based and concrete-based materials have desirable features for construction works, it is important to pay good attention to their areas of applications in different jurisdictions. It is important to ensure the application of the materials in areas where they have highest strengths. When compared to wood, high strength concrete may not decay as wood-based materials, especially for certain foundation works. While the lightweight of wood structures is coveted to minimize impacts on residents in earthquake prone areas, improvement of research efforts to develop technologies to improve the fire resistivity of wood-based building products will be commendable. There is a need for LCA evaluation for construction materials in different localities globally to determine the best material for use, considering local conditions, availability of materials, and other environmental impacts that are associated with long distance transportation of construction materials. This study recommends that material manufacturers and building contractors pay attention to LCA results to evaluate areas for continuous improvement. All building contractors should pay adequate attention to material selection in relation to LCA results for various construction locations. This study recommends continuous research effort not only in reduction of the immediate environmental impacts from material extraction and production but also in the reduction of long-term impacts through extended lifespan of various materials. With technological advancements and improved efficiency in material production and the associated energy requirement, results of LCA may change from time to time. This study recommends a periodic review and comparison of environmental impacts that can be associated with a widespread use of different construction materials at various jurisdictions globally. Studies like this can help identify areas where great opportunities for improvement exist. These periodic studies can also help in material use planning for construction works. For example, a periodic evaluation of resource mining rate and resource depletion potential can help develop strategies to supplement certain construction material with other alternative construction material.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix

Table 8. Bill of material and total mass value for Material Group 1

Material (Group 1)	Unit	Total Quantity	Columns & Beams	Floors	Foundations	Roofs	Walls	Project Extra Materials	Mass Value	Mass Unit
#15 Organic Felt	m2	889.2291	0.0000	0.0000	0.0000	889.2291	0.0000	0.0000	0.6490	Tonnes
8" Normal Weight Concrete Block	Blocks	2,100.8300	0.0000	0.0000	0.0000	0.0000	2,100.8300	0.0000	37.2477	Tonnes
Aluminum Window Frame	kg	76.5468	0.0000	0.0000	0.0000	0.0000	76.5468	0.0000	0.0765	Tonnes
Ballast (aggregate stone)	kg	7,445.4545	0.0000	0.0000	0.0000	7,445.4545	0.0000	0.0000	7.4455	Tonnes
Blown Cellulose	m2 (25mm)	311.6251	0.0000	0.0000	175.0213	136.6037	0.0000	0.0000	0.1994	Tonnes
Cold Rolled Sheet	Tonnes	0.0323	0.0000	0.0000	0.0000	0.0000	0.0323	0.0000	0.0323	Tonnes
Concrete Benchmark CAN 25 MPa	m3	6.2697	0.0000	6.2697	0.0000	0.0000	0.0000	0.0000	14.6047	Tonnes
Concrete Benchmark CAN 30 MPa	m3	61.3366	26.0765	0.0000	35.2601	0.0000	0.0000	0.0000	142.9799	Tonnes
Concrete Brick	m2	168.0664	0.0000	0.0000	0.0000	0.0000	168.0664	0.0000	38.6553	Tonnes
Expanded Polystyrene	m2 (25mm)	24.8850	0.0000	0.0000	0.0000	0.0000	24.8850	0.0000	0.0179	Tonnes
Galvanized Sheet	Tonnes	0.2206	0.0000	0.0000	0.0000	0.2206	0.0000	0.0000	0.2206	Tonnes
Glass Fibre	kg	315.0000	0.0000	0.0000	0.0000	0.0000	315.0000	0.0000	0.3150	Tonnes
Glazing Panel	Tonnes	0.3600	0.0000	0.0000	0.0000	0.0000	0.3600	0.0000	0.3600	Tonnes
Grout-Coarse	m3	6.7313	0.0000	0.0000	0.0000	0.0000	6.7313	0.0000	14.3781	Tonnes
Laminated Veneer Lumber	m3	0.3333	0.0000	0.0000	0.0000	0.0000	0.3333	0.0000	0.1523	Tonnes
Mortar	m3	6.7847	0.0000	0.0000	0.0000	0.0000	6.7847	0.0000	12.8095	Tonnes
Nails	Tonnes	0.1201	0.0000	0.0000	0.0104	0.0803	0.0294	0.0000	0.1201	Tonnes
Precast Concrete	m3	11.2139	0.0000	11.2139	0.0000	0.0000	0.0000	0.0000	27.4291	Tonnes
Rebar, Rod, Light Sections	Tonnes	5.8026	4.9106	0.4093	0.0000	0.0000	0.4827	0.0000	5.8026	Tonnes
Roofing Asphalt	kg	4,997.6934	0.0000	0.0000	0.0000	4,997.6934	0.0000	0.0000	4.9977	Tonnes
Small Dimension Softwood Lumber, kiln-dried	m3	4.0464	0.0000	0.0000	0.0000	3.6320	0.4144	0.0000	1.7121	Tonnes
Softwood Plywood	m2 (9mm)	172.4225	0.0000	0.0000	0.0000	172.4225	0.0000	0.0000	0.7833	Tonnes
Solvent Based Alkyd Paint	L	2.7164	0.0000	0.0000	0.0000	0.0000	2.7164	0.0000	0.0020	Tonnes
Type III Glass Felt	m2	1,778.4583	0.0000	0.0000	0.0000	1,778.4583	0.0000	0.0000	0.9342	Tonnes
Welded Wire Mesh / Ladder Wire	Tonnes	0.3352	0.0000	0.1834	0.1518	0.0000	0.0000	0.0000	0.3352	Tonnes
Total mass value									**312.2602**	Tonnes

Table 9. Bill of material and total mass value for Material Group 2

Material (Group 2)	Unit	Total Quantity	Columns & Beams	Floors	Foundations	Roofs	Walls	Project Extra Materials	Mass Value	Mass Unit
#15 Organic Felt	m2	889.2291	0.0000	0.0000	0.0000	889.2291	0.0000	0.0000	0.6490	Tonnes
Aluminum Window Frame	kg	76.5468	0.0000	0.0000	0.0000	0.0000	76.5468	0.0000	0.0765	Tonnes
Ballast (aggregate stone)	kg	7,445.4545	0.0000	0.0000	0.0000	7,445.4545	0.0000	0.0000	7.4455	Tonnes
Blown Cellulose	m2 (25mm)	311.6251	0.0000	0.0000	175.0213	136.6037	0.0000	0.0000	0.1994	Tonnes
Concrete Benchmark CAN 25 MPa	m3	6.2697	0.0000	6.2697	0.0000	0.0000	0.0000	0.0000	14.6047	Tonnes
Concrete Benchmark CAN 30 MPa	m3	35.2601	0.0000	0.0000	35.2601	0.0000	0.0000	0.0000	82.1937	Tonnes
Cross Laminated Timber	m3	14.3881	0.0000	0.0000	0.0000	0.0000	14.3881	0.0000	6.8408	Tonnes
Expanded Polystyrene	m2 (25mm)	24.8850	0.0000	0.0000	0.0000	0.0000	24.8850	0.0000	0.0179	Tonnes
Galvanized Sheet	Tonnes	0.2206	0.0000	0.0000	0.0000	0.2206	0.0000	0.0000	0.2206	Tonnes
Glass Fibre	kg	315.0000	0.0000	0.0000	0.0000	0.0000	315.0000	0.0000	0.3150	Tonnes
Glazing Panel	Tonnes	0.3600	0.0000	0.0000	0.0000	0.0000	0.3600	0.0000	0.3600	Tonnes
GluLam Sections	m3	6.9967	6.9967	0.0000	0.0000	0.0000	0.0000	0.0000	3.2695	Tonnes
Hollow Structural Steel	Tonnes	0.1621	0.0000	0.0000	0.0000	0.0000	0.1621	0.0000	0.1621	Tonnes
Laminated Veneer Lumber	m3	0.3333	0.0000	0.0000	0.0000	0.0000	0.3333	0.0000	0.1523	Tonnes
Nails	Tonnes	0.1242	0.0000	0.0000	0.0104	0.0803	0.0335	0.0000	0.1242	Tonnes
Precast Concrete	m3	11.2139	0.0000	11.2139	0.0000	0.0000	0.0000	0.0000	27.4291	Tonnes
Rebar, Rod, Light Sections	Tonnes	0.4093	0.0000	0.4093	0.0000	0.0000	0.0000	0.0000	0.4093	Tonnes
Roofing Asphalt	kg	4,997.6934	0.0000	0.0000	0.0000	4,997.6934	0.0000	0.0000	4.9977	Tonnes
Screws Nuts & Bolts	Tonnes	0.0181	0.0000	0.0000	0.0000	0.0000	0.0181	0.0000	0.0181	Tonnes
Small Dimension Softwood Lumber, kiln-dried	m3	4.0464	0.0000	0.0000	0.0000	3.6320	0.4144	0.0000	1.7121	Tonnes
Softwood Plywood	m2 (9mm)	172.4225	0.0000	0.0000	0.0000	172.4225	0.0000	0.0000	0.7833	Tonnes
Solvent Based Alkyd Paint	L	2.7164	0.0000	0.0000	0.0000	0.0000	2.7164	0.0000	0.0020	Tonnes
Spruce Wood Bevel Siding	m2	422.5670	0.0000	0.0000	0.0000	0.0000	422.5670	0.0000	2.0283	Tonnes
Type III Glass Felt	m2	1,778.4583	0.0000	0.0000	0.0000	1,778.4583	0.0000	0.0000	0.9342	Tonnes
Water Based Latex Paint	L	227.2642	0.0000	0.0000	0.0000	0.0000	227.2642	0.0000	0.1704	Tonnes
Welded Wire Mesh / Ladder Wire	Tonnes	0.3352	0.0000	0.1834	0.1518	0.0000	0.0000	0.0000	0.3352	Tonnes
Total mass value									**155.4513**	Tonnes

Table 10. Bill of material and total mass value for Material Group 3

Material (Group 3)	Unit	Total Quantity	Columns & Beams	Floors	Foundations	Roofs	Walls	Project Extra Materials	Mass Value	Mass Unit
#15 Organic Felt	m2	889.2291	0.0000	0.0000	0.0000	889.2291	0.0000	0.0000	0.6490	Tonnes
Aluminum Window Frame	kg	76.5468	0.0000	0.0000	0.0000	0.0000	76.5468	0.0000	0.0765	Tonnes
Ballast (aggregate stone)	kg	7,445.4545	0.0000	0.0000	0.0000	7,445.4545	0.0000	0.0000	7.4455	Tonnes
Blown Cellulose	m2 (25mm)	311.6251	0.0000	0.0000	175.0213	136.6037	0.0000	0.0000	0.1994	Tonnes
Concrete Benchmark CAN 25 MPa	m3	6.2697	0.0000	6.2697	0.0000	0.0000	0.0000	0.0000	14.6047	Tonnes
Concrete Benchmark CAN 30 MPa	m3	35.2601	0.0000	0.0000	35.2601	0.0000	0.0000	0.0000	82.1937	Tonnes
Cross Laminated Timber	m3	14.3881	0.0000	0.0000	0.0000	0.0000	14.3881	0.0000	6.8408	Tonnes
Expanded Polystyrene	m2 (25mm)	24.8850	0.0000	0.0000	0.0000	0.0000	24.8850	0.0000	0.0179	Tonnes
Galvanized Sheet	Tonnes	0.2206	0.0000	0.0000	0.0000	0.2206	0.0000	0.0000	0.2206	Tonnes
Glass Fibre	kg	315.0000	0.0000	0.0000	0.0000	0.0000	315.0000	0.0000	0.3150	Tonnes
Glazing Panel	Tonnes	0.3600	0.0000	0.0000	0.0000	0.0000	0.3600	0.0000	0.3600	Tonnes
Hollow Structural Steel	Tonnes	0.1621	0.0000	0.0000	0.0000	0.0000	0.1621	0.0000	0.1621	Tonnes
Laminated Veneer Lumber	m3	6.6769	6.3436	0.0000	0.0000	0.0000	0.3333	0.0000	3.0517	Tonnes
Nails	Tonnes	0.1242	0.0000	0.0000	0.0104	0.0803	0.0335	0.0000	0.1242	Tonnes
Precast Concrete	m3	11.2139	0.0000	11.2139	0.0000	0.0000	0.0000	0.0000	27.4291	Tonnes
Rebar, Rod, Light Sections	Tonnes	0.4093	0.0000	0.4093	0.0000	0.0000	0.0000	0.0000	0.4093	Tonnes
Roofing Asphalt	kg	4,997.6934	0.0000	0.0000	0.0000	4,997.6934	0.0000	0.0000	4.9977	Tonnes
Screws Nuts & Bolts	Tonnes	0.0181	0.0000	0.0000	0.0000	0.0000	0.0181	0.0000	0.0181	Tonnes
Small Dimension Softwood Lumber, kiln-dried	m3	4.0464	0.0000	0.0000	0.0000	3.6320	0.4144	0.0000	1.7121	Tonnes
Softwood Plywood	m2 (9mm)	172.4225	0.0000	0.0000	0.0000	172.4225	0.0000	0.0000	0.7833	Tonnes
Solvent Based Alkyd Paint	L	2.7164	0.0000	0.0000	0.0000	0.0000	2.7164	0.0000	0.0020	Tonnes
Spruce Wood Bevel Siding	m2	422.5670	0.0000	0.0000	0.0000	0.0000	422.5670	0.0000	2.0283	Tonnes
Type III Glass Felt	m2	1,778.4583	0.0000	0.0000	0.0000	1,778.4583	0.0000	0.0000	0.9342	Tonnes
Water Based Latex Paint	L	227.2642	0.0000	0.0000	0.0000	0.0000	227.2642	0.0000	0.1704	Tonnes
Welded Wire Mesh / Ladder Wire	Tonnes	0.3352	0.0000	0.1834	0.1518	0.0000	0.0000	0.0000	0.3352	Tonnes
Total mass value									**155.0811**	Tonnes

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