# The Environmental Cost of Hidden Waste in Design

Adekunle O. Mofolasayo
Civil and Environmental Engineering Department, University of Alberta, Edmonton, Canada
Email: madekunl@ualberta.ca

Abstract—Sustainable building design and construction strategies is a good approach to address the concern about environmental impacts of construction. There are some environmental impacts that can be avoided in the design of buildings. Hidden waste in building design can result in avoidable environmental impacts. Avoidance of hidden waste requires an evaluation of various designs patterns and the associated (environmental, social and economic) cost for humanity. This study reviews how the choice of design patterns of some sections (roof panels, joists, and beams) of a multi-family building design can result in various amount of material usage and consequent environmental impacts. An earlier study showed that for the same building area, various design choices would require varied amount of building material selection to satisfy the design code. This study indicates that the varied material quantity for the same building area results in varied environmental impacts. At the design stage, it is recommended that design professionals consider various design patterns to avoid hidden waste and to minimize environmental impacts that may originate from the building design. A documentation to show that various design patterns were considered during the design process (before selection of a design that is both safe and that imbibes the principle of sustainable building design) will be desirable.

Keywords—sustainable building design, waste minimization, hidden waste, design waste, environmental impacts, life cycle analysis, material specifications

## I. INTRODUCTION

Construction operations have been one of the pillars of modern civilization. Moreover, some concerns have been raised about the impact of construction works on the environment. Construction is considered as one of the major sources of environmental pollution in the world (Zolfagharian et al., 2012). Meanwhile, construction is essential to provide conducive accommodation and facilities to improve standard of living in different places. In recent years, there has been more interest in development of new and more suitable ways of constructing buildings, most especially, industrial and large commercial buildings (Svortevik et al., 2020). Designers globally are making efforts to minimize the impacts of their buildings on the environment (Mithraratne and Vale, 2004). Life cycle analysis (LCA) of construction operations (a process in which environmental impact of the processes that are involved in the lifecycle of structures are evaluated) is needed to continue to reap the benefit of construction works and ensure a minimization of the impact of construction operations on the environment. LCA is one of the methods to measure the sustainability of construction projects âYDMOHQND DQG ..Life Cycle VNi Analysis (LCA) is increasingly being used as a decision-making tool to support the choices of structural systems (Moncaster, et al., 2018). Environmental impacts categories that are evaluated in life cycle analysis includes: Ozone depletion, climate change, terrestrial acidification, fresh water eutrophication, marine eutrophication, photochemical oxidant formation, particulate matter formation, water depletion, metal depletion, and fossil depletion (Pittau, et al., 2019). Environmental impacts are often classified into three parts (i.e., impacts on atmosphere, water and earth). Global warming potential, Ozone depletion potential and Photochemical Ozone creation potential are classified under the impacts on the atmosphere. Acidification potential and Eutrophication Potential are classified under impacts on water. Depletion of Abiotic resources (elements) and depletion of abiotic resources (fossil fuels) are classified under impacts on earth. Photochemical ozone creation potential occurs from sunlight effect on nitrogen oxides, volatile organic compounds and hydrocarbons to produce an air pollution referred to as smog. Ozone depletion potential (caused by human made air pollution) is the potential for a compound to cause damage to the stratospheric ozone layer that protects the earth from ultraviolent radiation that is harmful to life. Global warming potential is referred to as the global changes in the weather patterns that occurs as a result of release of greenhouse gases into the atmosphere. Eutrophication potential is the potential for excessive nutrients to result in increase of the growth of algae in lakes, whilst blocking the underwater penetration of sunlight that is needed to produce oxygen, thereby resulting in the loss of aquatic life. Acidification potential results from human made emissions, decreasing pH and increasing the acidity of oceans, lakes, streams and rivers, (resulting in pollution of ground water whilst causing harm to aquatic life). Depletion of Abiotic resources (fossil fuel) refers to the decrease in the quantity of non-renewable hydrocarbon resources like coal and oil (as a result of human activity). Depletion of abiotic resources

---

Manuscript received November 15, 2022; revised December 14, 2022; accepted January 25, 2023; published March 8, 2023.

doi: 10.18178/joams.11.1.1-10

(elements) refers to the decrease in the availability of non-renewable resources like metals that are on the periodic table (AWC and CWC, 2020). Resource use and the environmental impacts that are associated with a building over its life cycle can be reduced if the environmental aspects are evaluated at the early planning stage (Schlegl et al., 2019).

### A. Impacts of Different Construction Process

From a study on “environmental impacts assessment on construction sites”, Zolfagharian et al., (2012) reported that noise pollution, dust generation with construction machinery and transportation resource are the greatest environmental impacts in Malaysia. Darnell (1976) mentioned that human activities are destroying the wetlands of America at a rate that is a cause for alarm. Erosion was said to be rampant and widespread. Another study (Ametepey and Ansah, 2014) indicated that among other things, greenhouse gas emissions, electricity consumption, dust generation from machinery, consumption of raw materials, vibration generation and noise are some of the environmental impacts of construction. Offsite production offers a prospect to help reduce some of the environmental impacts from construction activities. Offsite production refers to a construction process in which substantial parts of the construction works have been completed prior to installation on-site (Blismas et al., 2007). A combination of factors such as cost, productivity, quality, time, health and safety form the major motivation for the use of offsite modern methods of construction by household builders; the challenges that face wider acceptance includes longer lead-in time, delayed planning process, interface problems, high capital costs, and current manufacturing capacity (Pan et al., 2007). Oftentimes, the decision to choose one method of construction over another that involves offsite production (OSP) are based on cost, rather than value (Blismas et al., 2007). The study furthermore noted that acceptance of offsite construction will not improve unless there is a serious method for benefit analysis of OSP, that accounts for site-specific complexities. While different construction processes can affect the efficiency of construction and consequently the environmental cost of the construction, considerable opportunities to minimize the environmental impact of construction exist in the design process. This study highlights some of the opportunities for reduction of the environmental impact of construction from varied pattern of the design for a building.

TABLE I. LCA SYSTEM BOUNDARY MODULES (ADAPTED FROM AWC & CWC, 2020)

| Stages | Codes | Activities |
|---|---|---|
| Production stage | A1 | Extraction and production at upstream |
| | A2 | Transportation to facility |
| | A3 | Manufacturing |
| Construction stage | A4 | Transportation to site |
| | A5 | Installation |
| Use Stage | B1 | Use |
| | B2 | Maintenance |
| | B3 | Repair |
| | B4 | Replacement |
| | B5 | Refurbishment |
| | B6 | Operational energy use (during use of the product/facility) |
| | B7 | Operational water use (during use of the product/facility) |
| End of life stage | C1 | Deconstruction |
| | C2 | Transport |
| | C3 | Waste processing |
| | C4 | Disposal |
| Benefits and loads beyond the system boundary | D | Reuse, recovery, Recycling potential. |

## II. METHODOLOGY

A building design having 3 different patterns (orientations) was examined to see the impact of the design patterns on the environmental performance of the buildings. Mofolasayo, (2022) showed that the different building patterns result in varied material requirement. Results from the environmental product declaration for the materials and an LCA software (ATHENA) was used to evaluate the environmental impact of the different material specifications for varied design patterns (from cradle to gate). The system boundary for the environmental impacts using both environmental product declaration (EPD) and ATHENA software is the production stage (i.e., A1 - A3 from product extraction to manufacturing). Further analysis was done to evaluate the effect of different design patterns on the environmental impacts to the construction stage (A4 - A5), using ATHENA LCA software. Future study is recommended on life cycle impacts from cradle to grave. Table I shows various stages in the LCA system boundaries. Fig. 1 showed the project methodology for the study. Stage 1 to 4 was done in a previous study (Mofolasayo, 2022).

Figure 1. Project methodology.

## B. The Construction Materials

This analysis focused on three construction materials (Glulam, Cross laminated timber, CLT and Softwood lumber). Wood is a material of choice for construction works due to its renewable nature. Among the construction materials selected for evaluation, Glulam and CLT are classified under mass timber category. Mass timber construction is a building process in which engineered wood products are used as the primary structural material of choice (Kremer and Symmons, 2015). MTC involves the use of different types of massive wood planar or frame elements for core elements, walls, roofs, floors, and partitioning of a building. Other mass timber (not included in this analysis) includes: structural composite lumber (SCL), Nail laminated timber (NLT), Dowel Laminated timber (DLT), Interlocking cross-laminated timber (ICLT), Cross nail laminated timber, CNLT (Smith et al., 2018). Mass timber construction is being used in an increasing number of building projects to replace concrete and steel (Crawford and Cadorel, 2017).

## C. Environmental Product Declaration, EPD for the Selected Construction Materials

Environmental product declarations are documents that presents the environmental impacts of various materials with a specified system boundary. EPDs can complement but cannot be used to set performance threshold nor replace tools and certifications that are designed to address environmental or social performance benchmarks (AWC, and CWC, 2020). Sheets with environmental information that can be based on tools such as life cycle assessment and/or environmental Product declarations (EPD) are one of the tools that are recommended by the United Nations environmental program (UNEP) to assist green public procurement. These can help with choice and comparison between alternatives (Timm and Passuello, 2021).

## D. EPD for North American Glulam

Glulam is an engineered wood product in which two or more layers of lumber are glued together in the direction parallel to the grain of the wood. This bond results in an engineered wood product with high structural strength that is used for posts, beams and mass timber structure (AWC and CWC, 2020). The American Wood Council and the Canadian Wood Council presented an environmental product declaration (EPD) for North American glued laminated timber. The EPD covered three major LCA stages: Extraction and upstream production (A1), transport of lumber and resin to facility (A2) and manufacturing (processing and packaging of) Glulam. EPD by American Wood Council (AWC) and Canadian Wood Council (CWC) showing an industrial average for 1 m³ of glulam produced in North America gives the results in Table II below. The certification period is 2020 – 2025.

TABLE II. EPD SUMMARY FOR 1M³ NORTH AMERICAN GLULAM (ADAPTED FROM AWC & CWC, 2020)

| Area of impact | Impact Category | Values | Tool /Methods |
|---|---|---|---|
| Atmosphere | Global Warming Potential (KgCO2-Equiv) | 137.19 | Traci |
| | Ozone Depletion Potential (Kg CFC11- Equiv.) | 5.97E-06 | Traci |
| | Photochemical Ozone Creation Potential (KgO3-Equiv) | 147.81 | Traci |
| Water | Acidification Potential (Kg SO2-Equiv) | 4.36 | Traci |
| | Eutrophication Potential (Kg-N-Equiv.) | 0.83 | Traci |
| Earth | Fossil fuel depletion (MJ, Surplus) | 217.09 | Traci |
| | Depletion of Abiotic Resources (Fossil Fuels), MJ | 1,864.65 | CML |

## E. EPD for Softwood Lumber

Softwood lumber is used in construction of residential and commercial buildings, furniture manufacture and others. The functional unit for the North American softwood lumber is 1m³. The system boundary for the softwood lumber is also stages A1 to A3 of LCA process (resource extraction to product manufacturing). The validity period is 5 years from July 1, 2020. Table III shows the environmental impacts from North American softwood lumber (AWC and CWC, 2020).

TABLE III. THE ENVIRONMENTAL IMPACTS FOR SOFTWOOD LUMBER (ADAPTED FROM AWC, & CWC, 2020)

| Area of impact | Impact Category | Values/m³ |
|---|---|---|
| Atmosphere | Global Warming Potential (KgCO2-Equiv) | 63.12 |
| | Ozone Depletion Potential (Kg CFC11- Equiv.) | 2.80E-06 |
| | Photochemical Ozone Creation Potential (KgO3-Equiv) | 13.68 |
| Water | Acidification Potential (Kg SO2-Equiv) | 0.52 |
| | Eutrophication Potential (Kg-N-Equiv.) | 0.25 |
| Earth | Fossil fuel depletion (MJ Surplus) | 101.51 |
| | Depletion of Abiotic Resources (Fossil Fuels), MJ, LHV | 83337 |

## F. EPD for Cross Laminated Timber, CLT

Cross-laminated timber is an engineered wood product that is made by attachment of wood layers in an alternating form using strong adhesive (at an adequate pressure). The orientation of the layers are perpendicular to adjacent layers (Dong et al., 2020). FP innovations (2018) provided a cradle to gate environmental product declaration (EPD) for cross-laminated timber for three of the LCA stages. (A1: extraction of raw materials and processing; A2: transportation of raw materials from an extraction site to a manufacturing site; and A3: manufacturing of the wood construction product, including packaging). This is presented in Table IV. The 5-year certification period for the EPD is 2018 ±2023.

TABLE IV. Environmental Performance of 1 $m^3$ of Cross Laminated Timber (Nordic X-Lam (TM)) by Life Cycle Stage (Absolute Values) - Adapted from FP Innovations (2018)

| Impact Category | Values/m3 |
|---|---|
| Global Warming (KgCO2 eq) | 121.89 |
| Ozone Depletion (Kg CFC-11 eq) | 1.79E-06 |
| Smog (KgO3 eq) | 35.53 |
| Acidification (Kg SO2 eq) | 1.19 |
| Eutrophication (Kg N eq.) | 0.11 |
| Fossil fuel (MJ, eq) | 1831.88 |
| Nuclear, MJ eq | 67.35 |
| Biomass, MJ eq | 261.74 |
| Other renewable MJ eq (solar wind, geothermal and hydro) | 625.78 |
| Material resource consumption | |
| Non-renewable materials, Kg | 38.84 |
| Renewable materials (wood), Kg | 406 |
| Fresh water, m3 | 0.26 |
| Waste generated | |
| Hazardous waste, Kg | 0 |
| Non-hazardous waste, Kg | 1629.05 |
| Feedstock energy, MJ (Higher heating value basis) | 8282.4 |

## G. The Design Patterns

Fig. 2 shows the patterns for the design of the roof panels. These patterns generated different material requirements. The design procedure and material selection for the roof panels, roof joists, beams and columns were presented in a previous work (Mofolasayo, 2022). The bill of materials for the present study was generated with ATHENA software. Athena software includes some additional quantities to account for material wastage. Hence, the volume of wood generated by the software is a little more than the actual volume calculated. This bill of material quantities is presented in Table V.

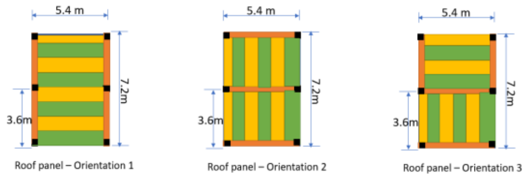

Figure 2. Orientations / patterns for the roof panels (Mofolasayo, 2022).

The glulam material selected for the beams are Glulam 20f-Ex D. fir. L 175mm × 494mm and Glulam 20f-Ex D. Fir. L 175mm × 456mm, while the glulam material selected for the column are Glulam 16c-E (D.Fir. L.): 175 × 152mm and Glulam 16c-E (D. Fir. L.): 175 × 190 mm. For this LCA, no distinction was made between the LCA for the different types of glulam. Further study is recommended to investigate any potential differences in the LCA for the production of various grades of glulam. The lumber materials selected for the roof joists are Douglas Fir Larch SS, 89 × 286mm and 38 × 286mm. While the cross-laminated timber, CLT material selected for the roof panels are Douglas Fir L. E2 1000 × 175 mm and 1000 × 105 mm. These material selections are presented in an earlier study (Mofolasayo, 2022). For Athena software, the construction waste factor for glulam and CLT is 0.01. Hence, the total glulam and CLT quantity is multiplied by 1.01 to get the net amount of wood. The construction waste factor for large dimension softwood lumber, kiln-dried is 0.05. Hence the total lumber quantity is multiplied by 1.05 to get the net amount for the analysis.

TABLE V. Bill of Material for the Three Design Patterns (Generated by Athena Software)

| Material | Unit | Total Quantity | | |
|---|---|---|---|---|
| | | Orientation 1 | Orientation 2 | Orientation 3 |
| Cross Laminated Timber | $m^3$ | 68.7204 | 41.2322 | 54.9763 |
| GluLam Sections | $m^3$ | 19.5625 | 19.5007 | 21.9804 |
| Large Dimension Softwood Lumber, kiln-dried | $m^3$ | 18.7005 | 8.19 | 14.1645 |

## H. Estimating Environmental Impacts from Environmental Product Declaration (EPD) for Materials

To use the EPD to estimate the environmental impacts for selected materials, the overall quantity of materials is multiplied by the environmental impact per unit from the EPD document. Note that this will be limited to the system boundary that is provided in the EPD document.

As indicated in a previous study (Zhang et al., 2013):

Emissions = Activity volume × emission coefficient

Software such as ATHENA, provides estimates of environmental impacts for certain geographical locations in North America. This can also be used to estimate the environmental impact from various design choices. Given that the environmental impact of design is often proportional to the quantity of material that is used, it is logical to note that designs that utilizes more material (of the same type) will yield more environmental impact. For global warming potential of wood, the overall impact is often reported in favor of wood material because wood materials help in sequestration of carbon. However, it should be noted that the environmental impact from wood will depend on how it is treated at the end-of-life stage.

Woods that are burnt at the end of the useful life of a building will no longer act as a storage for carbon; rather the carbon will be released to the atmosphere at that time (except a carbon capture technology is implemented for this process). Nakano et al., (2020) noted that the biogenic carbon that is locked in the building during its usage is 32% to the total GHG emissions of the building construction. Hence, a long-term use of the CLT buildings is recommended, because this carbon will eventually be released into the atmosphere at the end-of-life stage of the building. Table I shows the LCA stages. Having been provided an LCA for a stage of production, researchers/designers may look into individual components for other stages for a more comprehensive LCA output (i.e., when the system boundary of an EPD does not reach the desired stage for evaluation, researchers will have to go a step further to evaluate the environmental impacts for other activities.

## III. RESULTS AND DISCUSSION

The results from the environmental product declaration can be used to complement the result from ATHENA software. They both provide estimate of the environmental impact of the selected construction materials. Integration of lifecycle assessment benchmarks in the planning stage of a project is a potential measure to help reduce the environmental impact of a building over its life cycle (Schlegl et al., 2019). Table VI below shows the LCA output for the production stage for glulam used in the three patterns. The values/m$^3$ of glulam that were obtained from the EPD were multiplied by the quantity of glulam in the designs to obtain the estimated environmental impact from glulam.

Environmental Impact for selected member = (Impact value / m$^3$) from EPD × Volume of material from design

For example, for orientation 1 in the acidification potential, volume of wood is 19.5625m$^3$. Acidification potential from the EPD is 4.36 Kg SO$_2$-Equiv. /m$^3$ of glulam. Hence the acidification potential for glulam orientation 1 is (4.36 KgSO$_2$ eq. /m$^3$ × 19.5625m$^3$) = 85.29 KgSO$_2$ eq.

TABLE VI. ENVIRONMENTAL IMPACTS FROM GLULAM MEMBERS

| Area of impact | Impact Category | Values /m3 | Orientation. 1 | Orientation. 2 | Orientation. 3 |
|---|---|---|---|---|---|
| Atmosphere | Global Warming Potential (KgCO2-Equiv) | 137.19 | 2,683.78 | 2,675.3 | 3,015.49 |
| | Ozone Depletion Potential (Kg CFC 11- Equiv.) | 5.97E-06 | 0.00012 | 0.00012 | 0.00013 |
| | Photochemical Ozone Creation Potential (KgO3-Equiv) | 147.81 | 2,891.53 | 2882.39 | 3248.93 |
| Water | Acidification Potential (Kg SO2-Equiv) | 4.36 | 85.29 | 85.02 | 95.83 |
| | Eutrophication Potential (Kg-N-Equiv.) | 0.83 | 16.24 | 16.19 | 18.24 |
| Earth | Fossil fuel depletion (MJ, Surplus) | 217.09 | 4,246.82 | 4,233.4 | 4,771.73 |
| | Depletion of Abiotic Resources (Fossil Fuels) MJ | 1,864.65 | 36,477.19 | 36,361.94 | 40,985.81 |

Please, note that for an analysis of impacts from other designs, the quantity of material will have to be multiplied by the impact values/m$^3$ given in the EPD. The environmental impact for the construction stage will include the environmental impact from transportation to construction site, and the environmental impact from installation works on site. Environmental impacts from transportation to construction site can be reduced by locating manufacturing sites close to places where the construction will be done, or exploring transportation options with renewable energy. Using locally manufactured products will go a long way to help minimize environmental impacts from transportation processes. It has been found that CO$_2$ will increase if the distance of transport of the CLT is increased (Svortevik et al., 2020). While looking at the topic of environmental cost of hidden waste in design, it is important to bring the concept of sustainability to memory. Sustainability is multi-dimensional. This includes economic, social and environmental category. Given the economic and indirect social advantages that is generated from some energy that comes with environmental concerns. It is important to approach this aspect from a holistic point of view. Development of systems to capture and reprocess emissions of concern before they are introduced into the environment will go a long way to greatly reduce the environmental concerns from these materials. This approach will also allow the economic and social activities that comes with the energy development to continue. In the end, reserving non-renewable energy for use only for situations where it may not be economical or technologically feasible to use renewable energy will be a good approach.

TABLE VII. ENVIRONMENTAL IMPACTS FROM LUMBER MEMBERS IN THE DESIGN

| Area of impact | Impact Category | Values/m$^3$ | Orientation 1 | Orientation 2 | Orientation 3 |
|---|---|---|---|---|---|
| Atmosphere | Global Warming Potential (KgCO$_2$-Equiv) | 63.12 | 1,180.38 | 516.95 | 894.06 |
| | Ozone Depletion Potential (Kg CFC 11- Equiv.) | 2.80E-06 | 5.24E-05 | 2E-05 | 4E-05 |
| | Photochemical Ozone Creation Potential (Kg O$_3$ Equiv) | 13.68 | 255.82 | 112.04 | 193.77 |
| Water | Acidification Potential (Kg SO$_2$-Equiv) | 0.52 | 9.72 | 4.26 | 7.37 |
| | Eutrophication Potential (Kg-N-Equiv.) | 0.25 | 4.68 | 2.05 | 3.54 |
| Earth | Fossil fuel depletion (MJ, Surplus) | 101.51 | 1,898.29 | 831.37 | 1437.8 |
| | Depletion of Abiotic Resources (Fossil Fuels), MJ, LHV | 833.37 | 15,584.44 | 6825.3 | 11804 |

From Table VII above, the evaluation of EPD results showed that among the three design patterns, Orientation 2 has the least environmental impact in depletion of abiotic resources, global warming, ozone depletion, acidification, eutrophication, and photochemical ozone creation potential. For the global warming potential category, while Orientation 3 is 72.9% higher than Orientation 2, Orientation 1 is 128.3% higher than Orientation 2.

TABLE VIII. ENVIRONMENTAL IMPACTS FROM CLT MEMBERS IN THE DESIGN.

| Impact Category | Values /m$^3$ | Orientation 1 | Orientation 2 | Orientation 3 |
|---|---|---|---|---|
| Global Warming (KgCO$_2$ eq) | 121.89 | 8,376.33 | 5025.8 | 6701.1 |
| Ozone Depletion (Kg CFC 11 eq) | 1.79E-06 | 0.0001231 | 7E-05 | 1E-04 |
| Smog (Kg O$_3$ eq) | 35.53 | 2,441.64 | 1465 | 1953.3 |
| Acidification (Kg SO$_2$ eq) | 1.19 | 81.78 | 49.07 | 65.42 |
| Eutrophication (Kg N eq.) | 0.11 | 7.56 | 4.54 | 6.05 |
| Fossil fuel (MJ, eq) | 1831.88 | 125,887.53 | 75533 | 100710 |
| Nuclear, MJ eq | 67.35 | 4,628.32 | 2777 | 3702.7 |
| Biomass, MJ eq | 261.74 | 17,986.88 | 10792 | 14390 |
| Other renewable MJ eq (solar wind, geothermal and hydro) | 625.78 | 43,003.85 | 25802 | 34403 |
| Material resource consumption | | | | |
| Non-renewable materials, Kg | 38.84 | 2,669.10 | 1601.5 | 2135.3 |
| Renewable materials (wood), Kg | 406 | 27,900.48 | 16740 | 22320 |
| Fresh water, m$^3$ | 0.26 | 17.87 | 10.72 | 14.29 |
| Waste generated | | | | |
| Hazardous waste, Kg | 0 | 0 | 0 | 0 |
| Non-hazardous waste, Kg | 1629.05 | 111,948.97 | 67169 | 89559 |
| Feedstock energy, MJ (Higher heating value basis) | 8282.4 | 569,169.84 | 341502 | 455336 |

Table VIII indicates that Orientation 2 has the minimum environmental impact. Table IX shows a comparison of emissions to the atmosphere and to the water bodies for Orientations 1 to 3. Table IX also showed that Orientation 2 has the lowest environmental impacts among the environmental impact categories that were evaluated.

TABLE IX. EPD TOTALS FOR GLULAM, CLT AND LUMBER - (COMPARISON OF EMISSIONS TO ATMOSPHERE AND WATER FOR ORIENTATIONS 1 TO 3).

| Area of impact | Impact Category | Orientation 1 | Orientation 2 | Orientation 3 |
|---|---|---|---|---|
| Atmosphere | Global Warming Potential (KgCO$_2$-Equiv) | 12,240.48 | 8,218.05 | 10,610.62 |
| | Ozone Depletion Potential (Kg CFC 11- Equiv.) | 0.000292 | 0.000213 | 0.000269 |
| | Photochemical Ozone Creation Potential (Kg O$_3$-Equiv) | 5,588.99 | 4,459.42 | 5,396.01 |
| Water | Acidification Potential (Kg SO$_2$-Equiv) | 176.79 | 138.35 | 168.62 |
| | Eutrophication Potential (Kg-N-Equiv.) | 28.47 | 22.77 | 27.83 |

## A. Results from ATHENA Evaluation

Athena sustainable materials institute produced the Athena impact estimator software for buildings. This software is also used in the evaluation of the environmental impacts for the 3 different orientations in the design. Athena provides LCA evaluations for estimations in different geographical locations in North America. Calgary was selected for this evaluation, being the closest location that is available to the original location selected for the main design (Edmonton). Fig. 3 showed that Orientation 2 has the lowest impact in the global warming potential category.

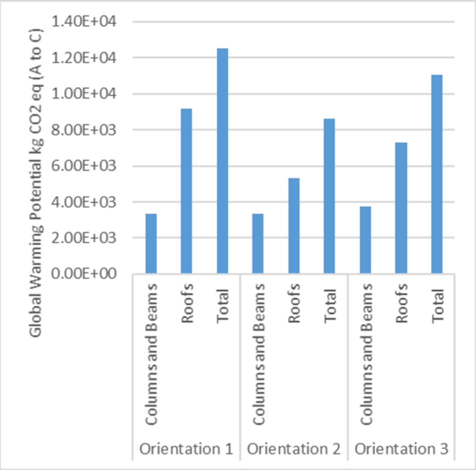

Figure 3. Global warming potential analysis by building sections- Results from Athena impact estimator (EI) for buildings (Stages: A to C- Material extraction to construction).

Fig. 4 also showed that orientation 2 has the lowest impact in the acidification potential category. The columns and beams have lesser impact than the roo sections.

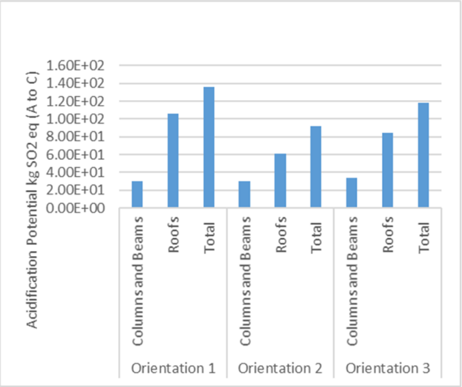

Figure 4. Acidification potential analysis by building sections: Results from Athena IE (A to C).

Orientation 2 has the lowest impacts in the HH particulate (Fig. 5) and the ozone depletion potential category (Fig. 6). Figs. 7 to 11 also showed that Orientation 2 has the lowest environmental impact.

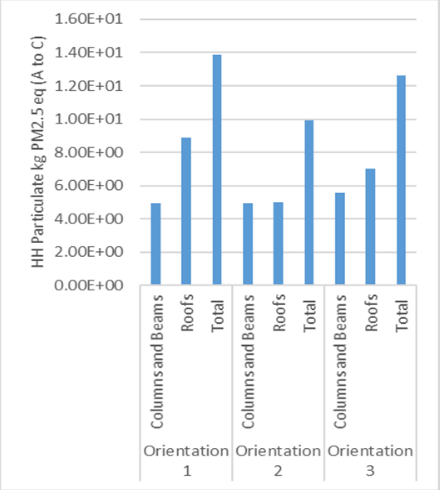

Figure 5. HH particulate analysis by building sections±Results from Athena impact estimator (A to C).

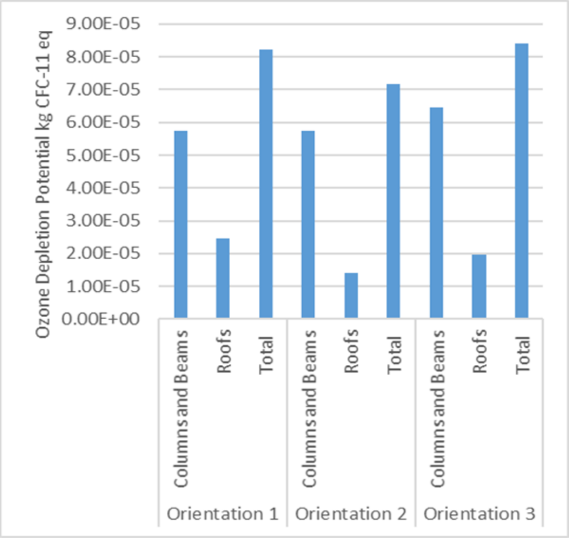

Figure 6. Ozone depletion potential by building sections±Results from Athena (A to C).

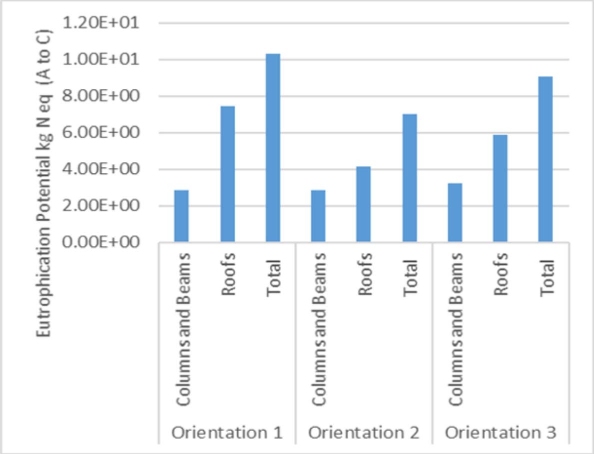

Figure 7. Eutrophication potential by building sections±Results from Athena (A to C).

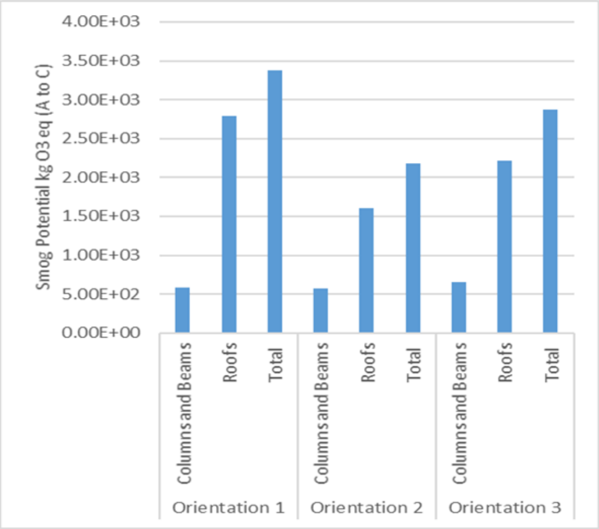

Figure 8. Smog potential by building section- Results from Athena Impact estimator (A to C).

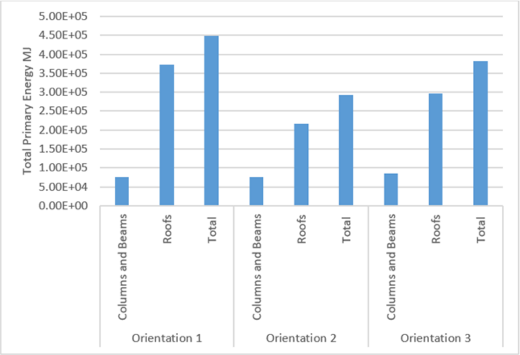

Figure 9. Total primary energy by building section. Results from Athena Impact estimator (A to C).

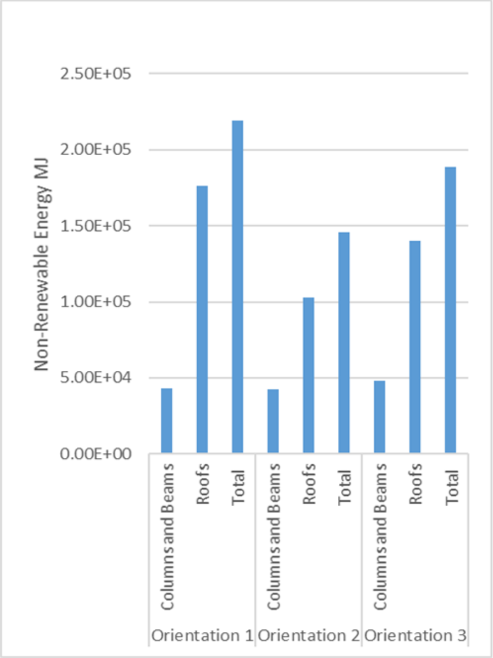

Figure 10. Non-renewable energy by building section. Results from Athena Impact estimator (A to C).

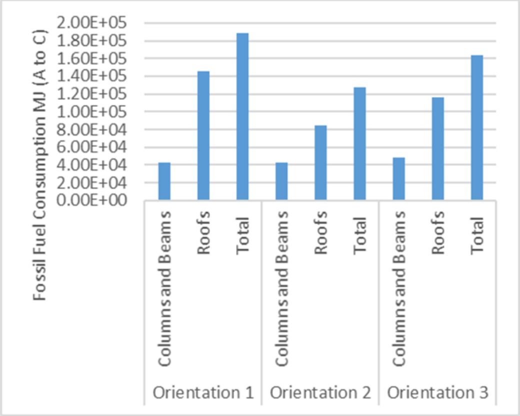

Figure 11. Fossil fuel consumption by building section. Results from Athena Impact estimator (A to C).

Table X shows the environmental impacts per square meter of the building. Ideally, this would be done for a total of all materials that goes into the construction of the building. The focus for this design was limited to roof panels, joists, beams and columns. Hence, this is not the overall impact for the entire building. However, it gives information on what effect design patterns may have on the environmental impacts of the building from cradle to gate (Material extraction to construction). Further analysis is recommended on the impacts to the end of life of the structure.

TABLE X. IMPACTS PER SQUARE METER OF BUILDING

| LCA Measures | Orientation 1 | Orientation 2 | Orientation 3 |
|---|---|---|---|
| Global Warming Potential, kg $CO_2$ eq | 3.22E+01 | 2.22E+01 | 2.84E+01 |
| Acidification Potential, kg $SO_2$ eq | 3.50E-01 | 2.35E-01 | 3.04E-01 |
| HH Particulate, kg PM $_{2.5}$ eq | 3.57E-02 | 2.55E-02 | 3.24E-02 |
| Eutrophication Potential, kg N eq | 2.65E-02 | 1.81E-02 | 2.34E-02 |
| Ozone Depletion Potential, kg $CFC_{11}$ eq | 2.11E-07 | 1.84E-07 | 2.17E-07 |
| Smog Potential, kg $O_3$ eq | 8.67E+00 | 5.62E+00 | 7.37E+00 |
| Total Primary Energy, MJ | 1.15E+03 | 7.53E+02 | 9.83E+02 |
| Non-Renewable Energy, MJ | 5.63E+02 | 3.74E+02 | 4.84E+02 |
| Fossil Fuel Consumption, MJ | 4.84E+02 | 3.27E+02 | 4.21E+02 |

The field of LCA is evolving and results from LCA analysis may vary with different conditions that may affect production, and choice of transportation system in various municipalities. Overall, the EPD and the software analysis can give an idea of the potential impacts from various design choices. Documentation of efforts to analyze environmental impacts from alternative designs will be useful in the quest to ensure that design and construction works consider sustainable building principles. A comprehensive life cycle analysis for a building will include all aspects of the substructures and superstructures.

## B. Comparison of LCA Results from ATHENA with That from EPD

LCA is increasingly being used as a decision-making tool to support the choices of structural systems, but lots of methodological decisions and wide variation in approach are not adequately described by LCA modellers. Hence, academic work on increasing accuracy and understanding of LCA of buildings is important. Varying methodological choices can change the results by an alarming factor - up to a factor of 10 or more (Moncaster et al., 2018). The densities that were specified for the structural members in the design portion of this work may not necessarily be the same as the ones that are used in the EPD or the impact estimator software. In a previous work (Moncaster et al., 2018), existing literature was reviewed to identify three key areas where methodological variations exist. The reported areas in that report are: the choice of coefficients, the choice of life-cycle stages, and the material boundaries of the physical elements that are in the assessment.

Fig. 12 ± Fig. 14 in the appendix compares some of the results from EPD with outputs from Athena software. It is obvious that the results are not the same, however, the progression of the results are similar. In regards to the progression, it can be said that although the results are not exactly the same, the results from the EPD complements the results from the LCA software used. Orientation 2 was found to have the lowest environmental impacts in both the EPD analysis as well as in the analysis using the Athena impact estimator for buildings. Hence, the LCA results either from using the EPD or using the software can provide a good comparison of environmental impacts of material selections for construction. Further work is recommended on standardization of methods for LCA to ensure a consistent result.

## IV. CONCLUSSION AND RECOMMENDATIONS

Construction operations has been one of the pillars of modern civilization. Moreover, some concerns have been raised about the impact of construction works on the environment. In the effort to minimize the impact of construction on the environment, life cycle analysis (a process in which environmental impact of the processes that are involved in the lifecycle of a material are evaluated) is employed. Opportunities to minimize environmental impacts of a construction project can best be achieved when an adequate lifecycle analysis is conducted in the planning and design stage (pre-construction), and adequate strategies to minimize the environmental impacts are incorporated throughout the life cycle of the project. To make the right choice in construction methods, there is need to ensure that the value that is offered by an alternate construction are clearly seen. Sustainability principles encourages the use of resources in a way that future generations can still have good access to the resources. This means that wastefulness should be avoided in all phases of design and construction. This study compared the environmental impact of three design patterns using environmental product declaration (EPD) documents and life cycle analysis software (Athena impact estimator for buildings). It was noted that although the results from the EPD are not the same with that from the software, the two methods gave consistent patterns that can help in selection of design pattern with the least environmental impacts. For this analysis, the design with orientation 2 showed the least environmental impacts. For a sustainable building design, design professionals should consider more than one design pattern before selecting the best design that is both safe, and in agreement with sustainable principles. Design results and presentations should always include an analysis of the environmental impacts of design alternatives and the justification for the chosen design. Hidden waste in design results in considerable environmental impacts. Some environmental impact reduction opportunities have been highlighted in this report. This report encourages a sustainability culture in design and construction processes (ensuring that alternative design patterns are evaluated, and designs with minimal environmental impacts are chosen-where feasible).

### A. Recommendations for Future Work

Further study is recommended on the environmental impacts during the use phase of the structure. Further study is also recommended for environmental impacts whilst considering various construction methods such as offsite construction and onsite construction for various municipalities. Comparison of environmental impacts from other alternative and innovative building materials is recommended. Further work is recommended on capturing of hazardous emissions and reconversion of these into materials that are beneficial for the ecosystem at large. These further studies should include research on capturing and reprocessing of emissions from industrial, automobiles and various machine outlets. To further evaluate the potential for reduction of environmental impacts in construction, future study is recommended on comparison of LCA for softwood lumber and mass timber for various design works.

## APPENDIX

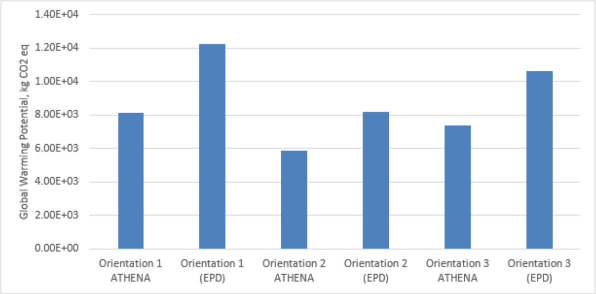

Figure A1. Comparison of global warming potential results from EPD and Athena impact estimator for buildings.

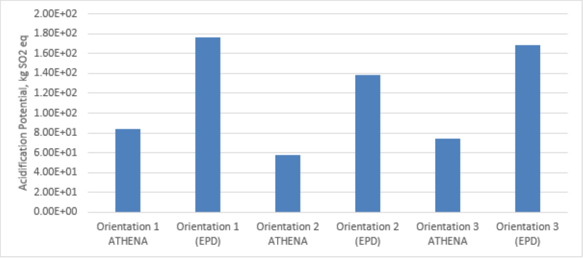

Figure A2 Comparison of acidification potential results from EPD and Athena impact estimator for buildings.

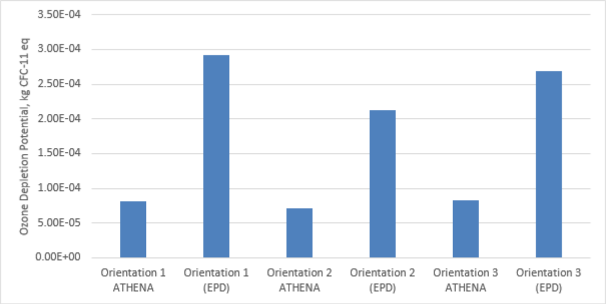

Figure A3 Comparison of ozone depletion potential results from EPD and Athena impact estimator for buildings.

## CONFLICT OF INTEREST

There is no conflict of interest for this article.

## REFERENCES

American Wood Council and Canadian Wood Council (2020). "Environmental Product Declaration-North American Glued Laminated Timber".

American Wood Council, (AWC) and Canadian Wood Council, (CWC). 2020. "UL Certified environmental product declaration- EPD transparency summary. Available: https://www.awc.org/pdf/greenbuilding/epd/AWC_TransparencySummary_NorthAmericanPlywood_20200715.pdf. accessed December 24, 2021.

American Wood Council, AWC & Canadian Wood Council, CWC. (2020). "North American Softwood Lumber-Environmental Product Declaration". Available: https://www.awc.org/pdf/greenbuilding/epd/AWC_EPD_NorthAmericanSoftwoodLumber_20200605.pdfAccessed December 27, 2021.

Ametepey, S. O. and Ansah, S. K. 2014. Impacts of construction activities on the environment: The case of Ghana. Journal of Construction Project Management and Innovation 4.

Blismas, N., Pasquire, C., and Gibb, A. 2007. Benefit evaluation for off-site production in construction. Construction Management and Economics, 24(2).

Crawford, R. H., and Cadorel, X. 19-22 June 2017. A framework for assessing the environmental benefits of mass timber construction. Procedia Engineering, 196: 831-846. Creative Construction Conference CCC, Primosten, Croatia.

Darnell, R. M. April 1976. Impacts of construction activities in wetlands of the United States. Ecological research series. Tereco Corporation, United States Environmental Protection Agency. EPA-600/3-76-045.

Dong, Y., Qin, T., Zhou, S., Huang, L., Bo, R., Guo, H., Yin, X. 2020. Comparative whole building life cycle assessment of energy saving and carbon reduction performance of reinforced concrete and timber stadiums-a case study in China. Sustainability, 12: 1566. doi:10.3390/su12041566.

FP Innovations. 2018. "Environmental Product Declaration- Nordic X-Lam (TM)". Available: https://library.fpinnovations.ca/en/viewer?file=%2fmedia%2fWP%2f7910.pdf#phrase=false&pagemode=bookmarks Accessed December 25, 2021.

Kremer, P. D., and Symmons, M. A. 2015. Mass timber construction as an alternative to concrete and steel in the Australia building industry: A PESTEL evaluation of the potential. International Wood Products Journal, 6(3): 138-147. DOI:10.1179/2042645315Y.0000000001

Mithraratne, N. and Vale, B. 2004. Life cycle analysis model for New Zealand houses. Building and Environment, vol. 39: 483-492.

Mofolasayo, A., Elimination of wastes in the design of buildings. 2022. Journal of Advanced Management Science, Vol. 10, (4): 94-99, doi: 10.18178/joams.10.4.94-99.

Moncaster, A. M., Pomponi, F., Symons, K.E., and Guthrie, P. M. 2018. Why method matters: Temporal, spatial and physical variations in LCA and their impact on choice of structural system, Energy & Buildings, 173: 389-398.

Nakano, K., Karube, M., and Hattori, N. 2020. Environmental impacts of building construction using cross-laminated timber panel construction method: A case of the research building in Kyushu, Japan. Sustainability, 12: 2220, doi:10.3390/su12062220

Pan, W., Gibb, A. G. F. and Dainty, A. R. J. 2007. Leading UK housebuilders' utilization of offsite construction methods. Building Research and Information, 36(1).

Pittau, F., Dotelli, G., Arrigoni, A., Habert, G., and Iannaccone, G. 2019. Massive timber building vs. conventional masonry building. A comparative life cycle assessment of an Italian case study, Sustainable Built Environment Conference (SBE 19 Graz). IOP Conf. Series: Earth and Environmental Science, 323. doi:10.1088/1755-1315/323/1/012016

Schlegl, F., Gantner, J., Traunspurger, R., Albrecht, S., and Leistner, P. 2019. LCA of buildings in Germany: Proposal for a future benchmark based on existing databases, Energy & Buildings, 194: 342-350.

Smith, R., Griffin, G., Rice, T., and Hagehofer-Daniell, B. 2018. Mass timber: Evaluating construction performance. Architectural Engineering and Design Management. Offsite Construction: Strategic Challenges and New Opportunities, 14(1-2).

Švajlenka, J., Kozlovská, M. 2020. Evaluation of the efficiency and sustainability of timber-based construction. Journal of Cleaner Production, vol. 259.

Svortevik, V. J., Engevik, M. B., & Kraniotis D. 2020. Use of cross laminated timber (CLT) in industrial buildings in Nordic climate: A case study. 2020 IOP Conf. Ser.: Earth Environ. Sci.: 410 012082

Timm, J. F. G., and Passuello, A. C. B. 2021. Potential use of environmental product declaration to support green public procurement in civil construction. Ambient. Constr., 21(2). https://doi.org/10.1590/s1678-86212021000200525. Available online at https://www.scielo.br/j/ac/a/NpSjqstXvczSfVbkgc3JZhd/?lang=pt# Accessed December 27, 2021.

Zhang, X., Shen, L., Zhang, L., 2013, Life cycle assessment of the air emissions during building construction process: A case study in Hong Kong. Renewable and Sustainable Energy Reviews, 17: 160-169.

Zolfagharian, S., Nourbakhsh, M., Irizarry, J., Ressang, A., & Gheisari M. 2012. Environmental impact assessment on construction sites. Construction Research Congress. ASCE.