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A COMPARATIVE LIFE CYCLE ASSESSMENT OF TALL BUILDINGS WITH ALTERNATIVE STRUCTURAL SYSTEMS: WOOD VS. CONCRETE

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Abstract: Life cycle assessment (LCA) has been a useful decision-making tool in sustainable building design, construction and building material selection. LCA can be a valuable tool in early design stages of a project to allow designers to quantify and compare environmental impacts of different building materials as well as after the building is constructed to assess new building material technologies that can inform future projects. Arising from a study of the construction of the world's tallest mass-timber building in Vancouver, this paper makes a comparison between two different construction technologies, wood and concrete, to understand the environmental benefits and drawbacks of each technology in terms of 9 LCA impact categories. Two 18-storey residential buildings in Vancouver, Canada, were considered for this study, a traditional cast-in-place concrete frame building and a mass-timber hybrid design using glulam and CLT. The scope of this study was limited to the assessment of foundations, structures, floors, columns, beams, and roofs. Floor plans, elevation views and material quantities were obtained from construction drawings and were entered into LCA software (Athena's Impact Estimator) to obtain the two buildings' LCA results. These indicated that in 8 of the 9 impact categories, the wood building had lower environmental impacts and in 1 impact category (total primary energy) the concrete building had lower environmental impact. The variation of the results of this study with other LCA studies is considered to be due to different building types, location, system boundary, scope of the study, variation in wood construction techniques, and different LCA methodology. This study was conducted as part of a course project and acts as a placeholder study for a more detailed LCA in the future.

1 INTRODUCTION

As the world's population continues to grow, the need for more buildings and infrastructure increases. However, this growing trend in the construction industry will have negative impacts on the environment. It is estimated that the building sector is responsible for one third of the total global greenhouse gas emission, primarily through the use of fossil fuels during the operational phases of a building (United Nations Environemnt Programme, UNEP, 2009). In Canada, the construction industry is estimated to account for 33% of energy production, 50% of the extracted natural resources, 25% of landfill wastes, 10% of airborne particulates and 35% of greenhouse gases (Lucuik 2005). However, these figures are rough estimates and the actual impact values are highly dependent on factors such as the materials used, manufacturing processes, transportation methods, construction practices and building usage patterns.

Despite the traditions of using concrete and steel as the primary building material for tall buildings, there has been an increased interest in using wood and wood-based materials for large-scale construction. This growth is driven by technical advances in the design, manufacture, and construction of engineered wood product structural systems, as well by recognition of the environmental advantages of wood as a renewable resource (CIRS 2016). In many low-rise stick-frame buildings, wood is the preferred building material due to its lighter weight, lower cost, higher construction speed and aesthetics. Results from comparative studies between concrete and wood buildings have also indicated that wood structures are environmentally less impactful (Guardigli, Monari and Bragadin 2011). With the application of wood in low-rise buildings being considered environmentally positive, interest using mass-timber for mid-rise and high-rise buildings is increasing. In 2009, British Columbia amended its building code to allow the design and construction of wood-framed buildings up to six storeys (Office of housing and Construction Standards 2009). In 2015, the University of British Columbia, along with the British Columbia Building and Safety Standards Branch, designed and developed site-specific regulations to construct the highest mass-timber hybrid building in the world with 18 storeys (CIRS 2016). With this growing interest, more comprehensive studies are needed to compare the benefits and drawbacks of wood in comparison with concrete as the primary building material for taller buildings. It is important to not only analyze, but also to quantify the environmental impacts of wood and reinforced concrete to facilitate informed decision-making.

This research aims to compare the environmental impacts of two high-rise buildings: a mass-timber hybrid building and a reinforced concrete frame building by conducting a life cycle assessment (LCA) on two case study buildings located on University of British Columbia’s Point Grey campus. The goal of this research is to obtain additional quantitative data to add to the existing LCA studies available for different size buildings with different occupancy types and in different locations. The ultimate aim of this and similar researches is to provide reliable and accurate impact assessment data to officials, policy makers, designers, contractors, stakeholders and other decision makers to support informed material selection and decision making in future projects. It is unreasonable to expect LCA to provide fully accurate results on a single building. In reality, LCA is most useful when it is being used as a tool for comparing relative performance of alternatives. The results of LCA are not definitive and are open to interpretation. In fact, the value of LCA results depend on the knowledge and experience of the interpreter (O'Connor, et al. 2012). Depending on the type of the project, surrounding policies, location of the project, and existing environmental conditions, impact categories will weigh differently in decision making. For example, acidification potential impact category may be the most significantly weighed category in Alaska, whereas smog potential may be more of a concern in India.

This research provides a simple comparison of the life cycle environmental impacts of the two case study buildings. The comprising material of the buildings along with their quantities were identified, measured, and entered into the LCA software. The software then quantifies how much each building impacts the environment in terms of 9 different impact categories. The results are then interpreted to determine the advantages and disadvantages of each building material. A more detailed description of methodology is provided in section 4.

2 LITERATURE REVIEW

LCA has been used for assessing building performance since the late 1980s, but it has only become an active research area in the last decade (Robertson, Lam and Cole 2012). Many LCA documents exist that compare alternative structural material, such as wood, concrete, steel and brick. However, the scope of this literature review has been limited to studies that have either compared wood and concrete structural systems (exclusively, or among other alternatives), or have solely focused on wood and engineered wood products. The findings are presented here chronologically.

One of the earliest researches on LCA was produced by Cole and Kernan in 1996. Their research examined the total life cycle energy use of a three-storey office building in Vancouver and Toronto for wood, concrete and steel structural system alternatives. The study estimates the initial embodied energy and the recurring embodied energy for maintenance and operation. The results indicated that operating energy has the largest contribution in life cycle energy use. The study also concluded that the wood framed structure had a lower embodied energy compared to the concrete frame building by 5% (Cole and Kernan 1996). In 1999, Börjesson and Gustavsson calculated the primary energy use and carbon dioxide emissions from the construction of a multi-storey building with either a wood frame or a concrete frame. The results of the study indicated that when concrete frames were considered, the primary energy input (mainly fossil fuels) for construction was about 60-80% higher compared to wood framed buildings. The study also describes that the efficiency of wood products in reducing GHG emissions depends on differences in the production processes and also on how the wood waste is handled after demolition. If all the demolition wood is deposited in landfills, the net GHG balance is positive (i.e., GHG sources are greater than GHG sinks). If the demolition wood is used to replace fossil fuels, net GHG balance will be slightly positive and if some of the demolition wood is re-used in a new building instead of replacing fossil fuels, net GHG balance will be slightly negative (Börjesson and Gustavsson 1999). 3 years later, in response to this paper, Lenzen and Treloar published a paper claiming an underestimation in Börjesson and Gustavsson's calculations. They claimed that due to their process analysis method, the energy requirements and GHG emission calculations are underestimated by a factor of 2. However, they acknowledged Börjesson and Gustavsson's general conclusion that concrete framed buildings cause higher emissions still holds (Lenzen and Treloar 2002). With growing interest in LCA and advancements in wood and engineered wood products, the Consortium for Research on Renewable Industrial Materials (CORRIM) created a consistent database of environmental performance measures associated with the production, use, maintenance, re-use, and disposal of wood and non-wood materials used in light residential construction. Additionally, CORRIM developed a framework for decision makers to evaluate life-cycle environmental and economic impacts for alternative building material in competing or complementary applications (Consortium for Research on Renewable Industrial Materials 2004).

In more recent years, many studies have compared building construction material alternatives, specifically engineered wood materials with other alternatives for mid-rise buildings. In 2013, the University of British Columbia assessed the impact of multiple building material and cladding options for their Center for Interactive Research on Sustainability (CIRS) building project. Among the top five design alternatives, one option included an all-concrete system while four other options consisted of hybrid designs using wood and concrete. The results showed that the all-concrete option had a higher embodied energy, global warming potential, resource use, and air pollution index compared to all other four options. In 2011, Guardigli, Monari, and Bragadin assessed the environmental impact of two green buildings in Europe, an innovative wood structure and a reinforced concrete structure. Overall, the wood building consumed less energy compared to the concrete alternative. However, an important observation made in this study was that from a life-cycle point of view, the use of OSB panels should be limited, as they have a bigger contribution to the damage to human health from their carcinogen agents, and to the ecosystem from elements that provoke acidification and eutrophication (Gaurdigli, Monari and Bragadin 2011). Similarly, Robertson conducted a comparative LCA on two mid-rise laminated timber and reinforced concrete buildings. The assessment found that the heavy timber design showed a lower environmental impact in 10 out of the 11 studied impact categories. Most significantly, global warming potential was 71% less in the timber design building. Fossil fuel depletion was the only category in which the concrete design was superior (by 6%). The total embodied energy of construction material was also calculated for both buildings. The results were surprising and contradictory to other previous studies. The author related this discrepancy to different building type and size, the use of lightwood framing in the earlier studies as opposed to more sophisticated wood products in their study (glulam, CLT, etc.) and higher amounts of feedstock energy in the timber design (A. B. Robertson 2011).

Although the construction of tall buildings has increased in the past years, minimal studies have examined tall buildings from a life cycle perspective. One such study examined the potential of reducing GHG emissions by replacing tall steel and concrete buildings with timber structures. LCA was used to analyze four 3 to 21-storey buildings. The timber structures were found to have a lower climate change impact compared to reinforced concrete structures by 34-84%, assuming a sustainable harvest (Skullestad, Bohne and Lohne 2016).

3 CASE STUDY

At the time of this study, the tallest mass-timber hybrid building in the world (Brock Commons Phase 1) was under construction at the University of British Columbia's Vancouver Campus (CIRS 2016). The motivation behind this research was to evaluate how the tallest timber building compares environmentally to a similar building with a concrete frame. Therefore, a preliminary LCA was conducted on Brock Commons (wood) and Ponderosa Commons (concrete) to compare the benefits and drawbacks of each structural system. Ponderosa Commons Phase 2 was considered to be an ideal concrete building for comparison, as it has similar location, size, design, and use as Brock Commons. Both buildings are located on the University of British Columbia's Point Grey campus in Vancouver, British Columbia. Brock Commons is an 18-storey (53 meters) mass-timber hybrid student residence with a gross floor area of 15,120 m^2. The building's foundation, ground floor, stairs, and elevator cores are reinforced concrete, while the superstructure is composed of cross-laminated timber (CLT) floor panels supported on Parallel Strand Lumber (PSL) and glue-laminated timber (GLT) columns with steel connections (CIRS 2016). Ponderosa Commons phase 2 consists of an L shaped wing connected to a residential wing. However, for the purpose of this study, only the residential building is considered. Ponderosa's building is also an 18-storey (53 meters) student residence with a gross floor area of 15,574 m^2. The building is a typical tall reinforced concrete structure where the foundation, floors, columns, stairs and elevator walls are all reinforced concrete. The case study buildings' proximity, similar height and gross floor area along with their residential occupancy type ensured the validity of the building selection process (in fact, the floor plan for the Brock Commons building was based, in part, from the Ponderosa Commons building).

4 LIFE CYCLE ASSESSMENT

LCA is a technique for assessing the potential environmental aspects associated with a product by compiling an inventory of relevant inputs and outputs, evaluating the potential environmental impacts associated with those inputs and outputs, and interpreting the results of the inventory and impact phases in relation to the objectives of the study (ISO 2006). In this particular study, LCA was used to determine which structural system alternative produced lower environmental impacts throughout its life cycle. One of the features of LCA that separates this method from other assessment methods is that it focuses on multiple life cycle stages of a building, eliminating the risk of transferring one environmental problem from one stage of the life cycle to another.

The International Organization of Standardization (ISO) along with the Canadian Standards Association (CSA) have produced multiple documents outlining the steps necessary to conduct an LCA. This study has followed the suggested framework (Figure 1).

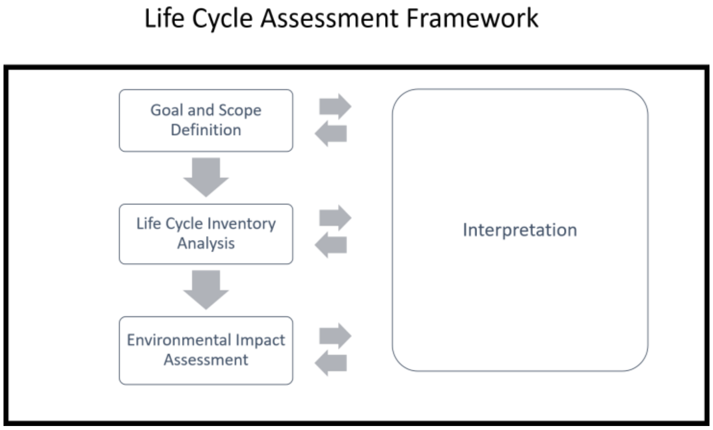

Figure 1: Life Cycle Assessment Framework (ISO14040:2006)

4.1 Goal and Scope Definition

The goal of this LCA is to compare the environmental benefits and drawbacks of mass-timber versus reinforced concrete as a tall building's primary building material. This study is intended for project officials, government decision makers, architects, engineers, and other stakeholders to make informed decisions when designing or deciding material alternatives for tall buildings, especially in North America.

The product system studied in this Brock Commons LCA is the foundation, slab-on-grade, first floor concrete columns, concrete cores, concrete stairs, glulam and PSL columns, CLT floors (including concrete protective layer, excluding other finishes), and roof. For Ponderosa Commons, the system study includes the foundation, slab-on-grade, concrete columns, concrete floors, concrete stairs and roof. Exterior walls of both buildings were prefabricated offsite and delivered to site for installation. Since it is relatively challenging to consider prefabricated components in the assessment software, this comparative study excluded the exterior walls from the scope of both buildings' assessment. The system boundary of the LCA was cradle-to-grave, from raw material acquisition, to construction phase, to building use phase, to end-of-life and disposal stages (See Figure 2 for detailed system boundary). For the purposes of the study, both buildings were assumed to have an estimated life expectancy of 60 years.

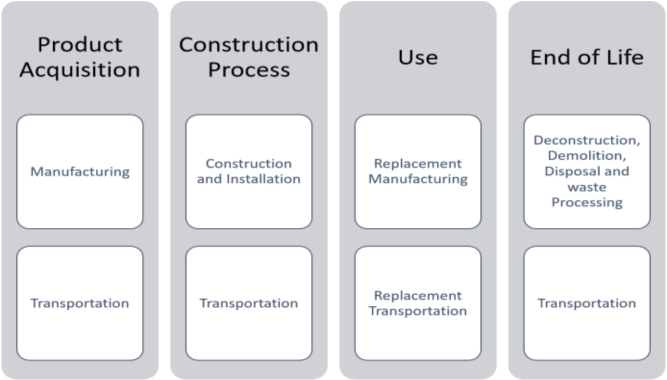

Figure 2 LCA System Boundary under Study

4.2 Life Cycle Inventory

Life Cycle Inventory (LCI) is the data collection portion of LCA. LCI is the accounting of everything involved in the building, from detailed tracking of all the flows in and out of the system, including raw material, energy, water, and emissions to air, water and land (Athena Sustainable Materials Institute n.d.). In this study, Athena Sustainable Materials Institute's LCI database was used to translate input flows into outputs.

4.3 Life Cycle Impact Assessment

Life cycle impact assessment (LCIA) is the step where inputted materials are analyzed by the LCI database to quantify environmental impacts. Athena's Impact Estimator for Buildings version 5 (IE4B) was used for this purpose. IE4B software uses TRACI (Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts) methodology to perform LCIA (Athena Sustainable Materials Institute 2014).

In order to obtain material quantity data to input into IE4B, material take-off was performed for each building from their respective floor plans and elevation plans using On-Screen Takeoff's Plan Viewer software. Material quantities for Brock commons and Ponderosa commons buildings were then entered into IE4B. The software then reported footprint data for the following environmental impact measures for both buildings: global warming potential, acidification potential, human health particulate, ozone depletion potential, smog potential, eutrophication potential, and fossil fuel consumption. The software also calculates total primary energy and non-renewable energy.

4.4 Assumptions and Limitations

Several assumptions and limitations exist that could have impacted the outcome of this research. The first ambiguity arose in the material take-off stage of the Ponderosa Commons. Ponderosa is comprised of an L-shaped building connected to the residential building under study. This connectivity of the buildings with additional underground floors under the courtyard made it difficult to separate the below-grade assemblies and define a clear boundary for the residential building.

Another simplification in the assessment was the exclusion of ancillary material such as nails, screws and other connections in the brock commons that don't exist to the same degree in the Ponderosa Commons project. Kellenberger and Althaus examined the importance of simplification in LCA of building components by conducting and comparing the LCA of an all-inclusive with a reduced (excluding minor elements) building component. The results showed that exclusion of ancillary material was significant (Kellenberger and Althaus 2009).

For both buildings, the exterior walls were excluded as they were prefabricated off site and IE4B cannot process prefabricated elements. The assumption that both buildings use similar prefabricated exterior wall panels justified their exclusion from the scope of the study.

There were also limitations associated with entering data into IE4B. For example, the software had restriction on the width of a footing. If a footing width of more than 1 m was entered, the software would show an error message. To overcome this limitation, the footings' dimensions were entered to the maximum value allowed and the rest of the footing (both the remaining concrete and its reinforcement) were entered manually in the "Extra Basic Material" section of the IE4B. Moreover, some dimensions could not be found on available design documents, and therefore the standard value from a similar building was assumed.

5 RESULTS

5.1 Impact Categories Results

After performing material take-off and entering these values into IE4B, numerical outputs were generated for each impact category. The results were then expressed per square meter of floor area to account for the slight variation in the two buildings' floor area. As shown in Figure 3, the Brock Commons building (wood) has a lower environmental impact in 8 of the 9 impact categories (global warming potential, acidification potential, HH particulate, eutrophication potential, ozone depletion potential, smog potential, non-renewable energy, and fossil fuel depletion), while the Ponderosa Commons building (concrete) has a lower impact in 1 of the impact categories (total primary energy). At a maximum, the HH particulate of Brock Commons was 38% less than Ponderosa, followed by ozone depletion potential with a reduction of 35%, global warming potential by 24%, acidification potential by 20%, smog potential by 17%, eutrophication potential by 12%, non-renewable energy by 8%, and fossil fuel consumption by 4%. Ponderosa commons' total primary energy was 11% less than the Brock commons. The results were normalized as a percentage in Figure 3, which also indicates which phase of the buildings' lifecycle has the largest overall contribution to each category. Phase A includes product manufacturing, product transportation, construction installation processes, and associated transportation. Phase B includes replacement manufacturing and transportation. Operational energy use is excluded from this phase, as energy data were not available. Phase C includes deconstruction, demolition, disposal and waste processing and associated transportation.

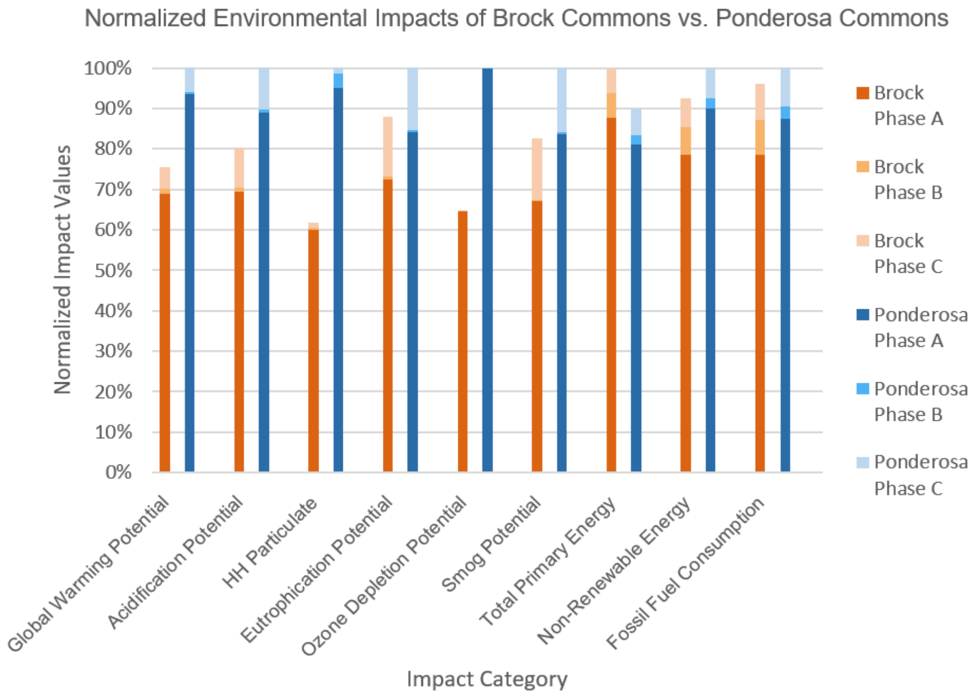

Figure 3 Life Cycle Impact Assessment Results

5.2 Interpretation of Results

The benefits of using wood as the primary structural material for a tall building can be seen in Figure 3, where Brock Commons has less environmental impact in 8 of the 9 categories. The global warming potential is a worldwide concern and perhaps one of the main reasons that the construction industry is shifting from concrete to wood as a primary building material. Therefore, it is not surprising that the Brock project has a lower global warming potential than Ponderosa. Wood is a renewable resource, with a neutral carbon balance. Carbon released into the atmosphere when wood is burnt will eventually be re absorbed by new tree growth, reducing the overall carbon emission in the life cycle of Brock Commons. Energy can also be recovered from demolition wood waste by the way of incineration. Moreover, wood and engineered wood material have a lower weight of shipping in both delivering the material to site and removing demolition waste from the site. Glulam columns and CLT panels are prefabricated offsite and therefore installation time is significantly less than traditional cast-in-place concrete and they consume less water and less electrical energy. In the demolition phase, wood buildings not only produce less waste, but they require less electrical energy as well (Pajchrowski, et al. 2014). These factors all contribute to Brock Commons' environmental advantage in the categories mentioned in section 5.1.

In all but one impact category (total primary energy), Brock Commons is environmentally more favourable. Embodied primary energy includes all energy, direct and indirect, used to transform or transport raw materials into products and buildings, including inherent energy contained in raw or feedstock materials that are also used as common energy sources (Athena Sustainable Materials Institute n.d.). IE4B considers total primary energy as the sum of the following energies: hydro, non-hydro renewable, coal, diesel, feedstock, gasoline, heavy fuel oil, LPG, natural gas, nuclear, and wood. The total primary energy is measured in Mega Joules (MJ) and the measured total primary energy for Brock Commons and Ponderosa Commons are 2607 MJ per square meter (or 242 MJ/square foot) and 2548 MJ per square meter (or 237 MJ/ square foot) respectively, bearing in mind the limited scope of the study.

The total primary energy of the Brock Commons is more than the total primary energy of Ponderosa Commons. Figure 4 breaks down the constituents of each building's embodied energy. From Figure 4, it can be seen that Brock Commons has a higher primary energy in Hydro, non-hydro renewable, feedstock, gasoline, LPG, and wood energy categories, resulting its total energy that surpasses Ponderosa's primary energy. From the primary energy types, wood, feedstock, and LPG have the most significant contribution. Since wood is not a primary material used in Ponderosa Commons, higher level of wood in Brock Commons primary energy calculations is justified. However, it is important to understand the significance of feedstock energy. Feedstock energy is the easily accessible potential energy contained in fuel resources that are extracted from earth. More specifically, they are the potential energy contained in engineered wood products (A. B. Robertson 2011). Comparing the feedstock energy of Brock Commons and Ponderosa Commons, it is apparent that Brock Commons has roughly 4.5 times of feedstock energy than Ponderosa Commons. This is due to the fact that wood material, specifically glulam and CLT panels, store potential energy within the wood fibres and within the fossil fuel-derived adhesive resins. This potential energy can be readily combusted and used as an energy source at the end of Brock Commons' service life. For Ponderosa Commons, it is not practical to obtain useful energy from concrete at the end of the building's service life (Robertson, Lam and Cole 2012).

The results obtained from the embodied energy comparison of the two case study buildings are significantly different from previous research results. In most of the previous studies, timber framed buildings generally tend to have lower embodied energy compared to concrete frame buildings. Comparing the results of different LCA studies is often challenging. Most of the previous studies examined light-wood framing technique, whereas in this study, glulam and CLT panels are the main components of the framing system. Moreover, each study has its own unique system boundary. The size, location, height, and functional use of buildings are different. The scope of each study is different. For example, this study only includes foundations, floors, columns, beams and roof. Other studies may include exterior walls, interior partitions, floor finishes, wall finishes, etc. Moreover, LCI databases are constantly updated to include the most accurate inventory data. Therefore, the time the study was done is also a factor in this variation. Also, different studies use different LCA tools to measure the embodied energy in a building, whereas in some tools, the total primary energy is calculated based on different energy types than IE4B. These variations

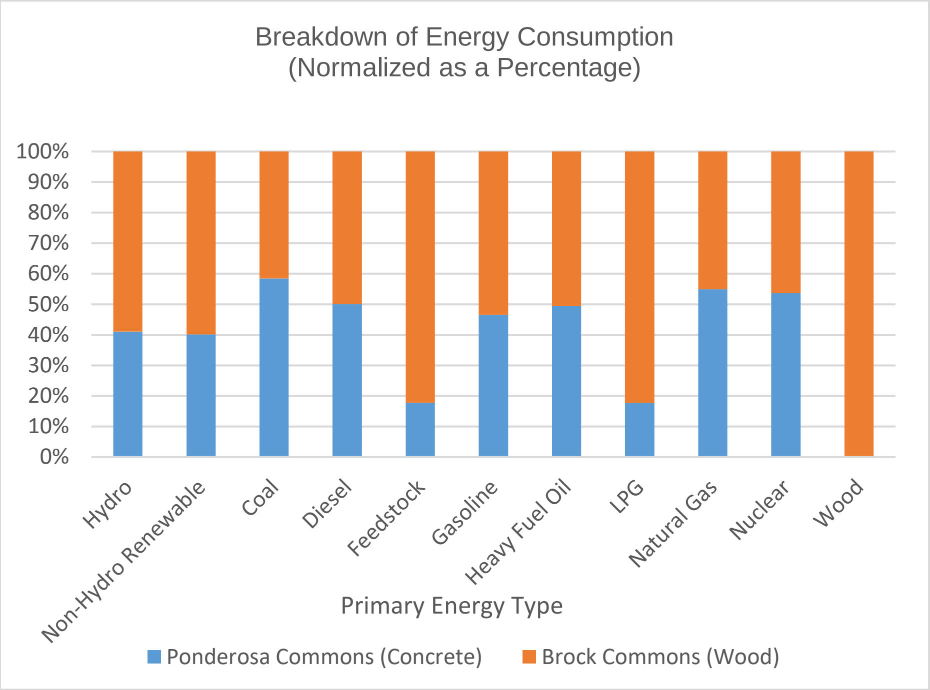

Figure 4 Total Primary Energy Breakdown

could all account towards the challenging nature of comparing different LCA study results. However, what can be said is that most of the impacts are a result of phase A activities (Figure 3). Manufacturing of building materials such as cement, wood products, and resins are more harmful to the environment compared to maintenance (Phase B) and deconstruction activities (Phase C).

5.3 Validation of Results

The results of this study can be validated in several ways. A preliminary LCA study has been done by the Brock Common's design team using Athena's EcoCalculator entry-level LCA tool. EcoCalculator provides designers with spreadsheets, where they can input estimated areas for each assembly and obtain a quick LCA for multiple design alternatives. EcoCalculator's comparison of the two case study buildings estimated comparable results. Given that the system boundary and considered assemblies in both studies may have been different, the similar magnitude of results provides an element of validation. The University of British Columbia's Center for Interactive Research on Sustainability is also currently conducting a detailed and comprehensive LCA and life cycle costing (LCC) on the two buildings.

Comparing this study with previous researches done in the past years showed similar results, except in embodied energy calculations. However, a study done in 2012 by Robertson yielded similar results in total primary energy category. In Robertson's research, the total embodied energy of a CLT/glulam framed building was nearly twice that of a concrete framed building. He attributed incomparability of his LCA results with other previous studies to variation in buildings, differences in energy accounting, and environmental modelling rationale. As technology grows and newer construction material is developed, it becomes more challenging to compare LCA result of conventional buildings with newer and more sustainable buildings.

6 CONCLUSION

It is important to evaluate a building's environmental performance, not only in the operational phase, but in all stages of its lifecycle. This study compared two 18-storey residential buildings with different structural material (wood and concrete) in Vancouver, Canada by means of LCA. The results of the study indicated that considering the system boundary and assemblies studied; it causes less environmental impact to use wood (specifically glulam and CLT) as the primary building material in 8 of the 9 impact categories. Moreover, the LCA results indicated that the Ponderosa Commons building (concrete) has a lower embodied energy compared to the Brock Commons building (wood), a difference of 11%. During the literature phase of the research, this result was not anticipated. However, comparing different LCA results becomes challenging due to the following reasons. 1) Most previous studies examined light wood framing technique whereas this study examined glulam and CLT framing technique, 2) Different studies are conducted around the world on buildings with different size, location, height, and purpose with different system boundaries, 3) Depending on the location of the building, different LCA tools are used and LCI availability varies, and 4) Different studies have different energy accountings. Additional research is needed to improve and compliment this research. Future studies should examine more assemblies in both buildings (including, but not limited to, interior and exterior walls). Also, each assembly should be examined in more detail to include finishes and ancillary material (i.e. connections). This study can support decision makers in choosing the right material for their project. However, this decision cannot be solely dependent on this or similar LCA results. A life cycle costing analysis needs to be done in parallel with LCA to make decisions based on a balance of environmental impacts of buildings and their corresponding cost.

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