Joint CSCE Construction Specialty & CRC Conference 2025
Conférence conjointe spécialisée en construction de la SCGC et CRC-2025

Montreal, Quebec
July 28-31, 2025 / *28-31 juillet 2025*

COMPREHENSIVE LIFE CYCLE ASSESSMENT OF BUILDING MATERIALS: A COMPARATIVE LCA OF HYBRID STEEL/TIMBER STRUCTURE WITH REDUCED TIMBER DESIGN

Abdulrahman Sati[1], Mohammed A. Alsati[1] and T.M. Froese[1]

[1] Dept of Civil Engineering, School of Engineering & Computer Science, University of Victoria, Victoria, BC, Canada

ABSTRACT: In Canada, it has been found that the construction sector contributes significantly to greenhouse gas emissions. To mitigate this impact, timber-based constructions have become increasingly favored due to their lightweight characteristics, expedited assembly, and environmental advantages. This research seeks to objectively validate the environmental impacts of hybrid structures through a case study building in Victoria, Canada. The focus of this study would be mainly to compare two different proposed designs for the same building. Design 1 evaluates the environmental impact of a structure predominantly composed of timber, whereas Design 2 substitutes glulam components (for instance, columns and beams) with steel elements whilst preserving a uniform floor configuration. Employing Athena software, the research quantifies the ecological footprints and determines that Design 2 exhibits a 5% elevated Global Warming Potential in comparison to Design 1. The results showed that Design 1, which contains a greater mass of timber, performed better across the entire life cycle of the project. The most significant difference between the two designs is at the beyond-building life stage (D), where Design 1 is projected to recover 197,000 kg CO_2 eq more than Design 2. These results indicate the necessity for further investigation into optimized hybrid structures that balance carbon reduction, resource efficiency, and long-term sustainability within the construction sector.

1. INTRODUCTION

Concerns over environmental pollution and CO_2 emissions have motivated the development of life-cycle-impact analysis for environmental profiling of different materials. Civil and building construction works account for 60% of the raw materials extracted from the lithosphere. Of this total, the building sector represents 40%, meaning they contribute to 24% of these global extractions (Bribián et al. 2011). In Canada, construction materials contribute significantly to greenhouse gas (GHG) emissions, especially within the building sector. Cement and concrete only account for 7% of global emissions, and their production represents a substantial portion of Canada's industrial emissions (Government of Canada, 2024). Construction Processes like manufacturing, transportation, and installation of steel, concrete, and glass require a large quantity of energy (Treacy 2020). Numerous studies have highlighted the advantages of using glue-laminated (glulam) and Cross-Laminated Timber (CLT) in the construction sector, particularly the positive effects on climate change, which has led to adoption by most policy & decision-makers for a sustainable future in the built environment. Life Cycle Assessment (LCA) is a systematic method for evaluating the environmental performance and potential impacts associated with a product, process, or service throughout its entire life cycle (ISO 2006). LCA helps decision-makers when selecting the optimal available option while minimizing the environmental impact of the buildings through their design or retrofit

(Bribián et al. 2009). A review of the literature on wooden buildings, Andersen et al., (2021) found that the median performance of 226 cases is between 3.9 and 4.7 kg CO_2e/m^2/year, depending on the building type. In comparison, a review study of 656 building cases of all types of materials by Röck et al. (2020) found a median performance between 6.7 and 17.3 kg CO_2e/m^2/year, indicating that wooden buildings, in general, perform better in LCA studies. In addition, wood has become the preferred building material choice due to its lightweight, lower cost, rapid construction capabilities, and aesthetic appeal. The findings were derived after comparative studies between concrete and wood applying LCA for different structural buildings (Guardigli et al., 2011). However, there is limited research that explores other environmental indicators such as effects on human health, ecosystem quality, and resource depletion—resulting from increased wood usage as a material substitution, which remains underexplored in the current literature (Cordier et al., 2021). In many cases, most studies focus on comparing the environmental impacts of wood structures to concrete structures, or steel structures to concrete structures. However, fewer studies have explored comparisons between mass timber and hybrid structures of the same building by varying the ratio of design components. This case is unique because the project was initially proposed as a heavy-mass timber design and later revised and constructed as a hybrid structure, presenting two fully developed and equivalent alternatives—an uncommon scenario in building design assessments. As participants in this project, having first-hand knowledge of how carbon considerations were integrated into the design decision-making process. This paper will demonstrate the rationale and approach behind incorporating carbon assessment into a practical context.

2. POINTS OF DEPARTURE

Life-cycle-oriented methods that were introduced as today's LCA were explored in the 1960s in collaboration between the academic and field industries. That was known as Resources and Environmental Profile Analysis (REPA) (Hunt et al. 1992) or Ecobalances until the term LCA became the norm in the 1990s. Early methods have been developed by the US and in Northern Europe. The method was inspired by material flow accounting, as the study focused on inventorying energy and resource use (e.g. crude oil, steel, etc.), emissions, and generation (Hauschild et al., 2018). During the early years of LCA's history, the beginning of addressing environmental concerns tended to follow public concerns. However, there was no consistency or harmonization of the applied methods. In this stage, the concern was on the generation of solid waste, especially in the US. In the following years, when the price of oil was fluctuating or high, energy use was the main focus of the studies. In this era, public concerns shifted towards emissions after being overlooked and controlled only by imposing some regulations. Only then the impact assessment methods started to develop to quantify the safe levels of energy emissions, such as the Swiss Ecopoint method in the 1980s (Ahbe et al. 1990).

In the 1990s, LCA impact assessment methods developed significantly, aiming to assess the environmental impacts comprehensively and thereby avoid burden shifting. The CML92 methodology, which was introduced in 1992 by Leiden University, was the first to cover a full range of midpoint impact categories (Heijungs et al. 1992). Sweden's EPS method and the Dutch Eco-indicator 99 emphasized damage to ecosystems and human health, marking a shift toward damage-focused models rather than midpoint impacts (Steen 1999a, b)(Goedkoop and Spriensma, 2000). Early LCA databases varied in data quality and standards, but the 2003 release of ecoinvent improved consistency across sectors. Parallel to process-based LCA, an advanced approach emerged, using input-output analysis to link economic data with environmental impacts (Leontief 2018).

Recently, many LCAs have been carried out in the construction sector by urban designers, property developers, architects, engineers, and consultants (Hellweg & Milà I Canals, 2014). Starting with (Buchanan & Honey 1994) who has conducted a study for a multi-story office building in New Zealand. The paper conducted a thorough study to analyze the energy consumption and CO_2 emissions associated with building construction using varied materials, specifically wood, steel, and concrete. The study assesses these materials from a life cycle perspective, examining the embodied energy and emissions of each and their impact on the building's overall environmental footprint. The main findings illustrated that wood generally has lower embodied energy and CO_2 emissions compared to steel and concrete. The study also provides specific guidance on optimal material allocation for structural elements to maintain high standards. For floor elements, concrete has the highest environmental impact, while timber has the lowest. For framing components, steel results in the greatest impact, whereas timber again shows minimal impact. Guggemos & Horvath, (2005) have implemented the LCA from another perspective, the paper has evaluated the impacts from all life-cycle phases, from “cradle to grave,” The aim was to quantify the energy use and the environmental emissions during the construction phase of two typical office buildings, one with a structural steel frame and one with a cast-in-place concrete frame. The findings were focused on four categories which evaluated the energy use over the phase of construction. overall, the concrete structural-frame construction has more associated energy use, CO_2, CO, NO_2, particulate matter, SO_2, and hydrocarbon emissions due to more formwork used, larger transportation impacts due to a larger mass of materials, and longer equipment use due to the longer installation process. On the contrary, the steel-frame construction has more volatile organic compound (VOC) and heavy metal (Cr, Ni, Mn) emissions due to the painting, torch cutting, and welding of the steel members. In addition, the paper recommended that, to reduce the energy emissions and environmental impacts, consideration should be given not only to materials selection but also to the construction equipment utilized. Another study focused on conducting a comparative “cradle-to-gate” life cycle assessment of a mid-rise office building located on the West Coast of Canada. Two scenarios were considered: a traditional cast-in-place reinforced concrete frame and a laminated timber hybrid design that utilized engineered wood products (cross-laminated timber (CLT) and glulam sections). The results indicated that the laminated timber building design offered a lower footprint in 10 of 11 assessed categories. Another study explained that the ability of wood materials, particularly glulam and CLT panels, to store potential energy is due to the structure of the wood fibers and the fossil fuel-based adhesive resins used in their manufacture. This potential energy can be readily combusted and used as an energy source at the end of service life, while it is not practical to obtain useful energy from concrete at the end of the building’s service life. (Teshnizi et al., 2018) provided valuable insights about the integration of sustainability and economic aspects in construction. By examining the environmental impacts and life cycle costs associated with two distinct residential towers at the University of British Columbia (UBC), Vancouver. The research highlighted several key findings; it revealed that material choices significantly affect the overall carbon footprint and energy consumption, with the use of sustainable materials leading to lower environmental impacts.

While numerous studies have compared the environmental impacts of wood versus concrete or steel versus concrete structures, relatively few have examined mass timber and hybrid structural systems within the same building by adjusting the proportions of design elements. In particular, this involves modifying the proportion of wood and steel used in the same building while ensuring the structural integrity remains uncompromised. This study examines how varying the wood-to-steel ratio in a structurally sound design influences the overall environmental impact.

3. METHODOLOGY

This study is grounded in the use of quantitative methods, specifically the LCA, which is categorized within the post-positivist research paradigm. This research seeks to objectively evaluate the environmental impacts of a case study located in British Columbia, Victoria. The focus of this study is to compare two different proposed designs for an institutional building. The new engineering expansion building model was used to help quantify and compare the environmental performance of the structural elements, focusing on key indicators such as human health, ecosystem quality, resource depletion, and greenhouse gas (GHG) emissions. The study employs Athena software, a well-established tool for calculating LCA. All the drawings and specifications were collected from a consultant firm located in Vancouver. A Building Information Modeling (BIM) model has been used to extract the bill of materials to ensure accurate material quantities for the LCA. In conclusion, a comprehensive comparative analysis was conducted involving the identical architectural layout but with varying proportions of structural elements to define the most optimal design configuration. More information will be defined in the next section.

3.1 Case Study

This study will shed the light on a touchable project that is currently under construction. This research aims to apply LCA to different contexts of skeleton material through the application of a case study located in Victoria, BC, the Engineering & Computer Science Expansion (ECSE) building project that will be connected to the south of the existing Engineering and Computer Science building at the University of Victoria. The project has a gross floor area of 6,334 m2 and consists of six stories. Structurally, the project was designed with a combination of concrete, steel, and timber. The foundation, elevator core at the foundation level, and slab-on-grade are made of reinforced concrete, while typical floors–two through six–and the upper-roof slab are constructed with CLT panels supported by a structural framework of glulam columns and steel framing. Additionally, all atrium stair bracings consist of steel and timber sections (Figure 1). Some modifications were applied by the designer to check the extent of sustainability of design changes. To reduce the volume of concrete, reinforced concrete column necks were replaced with H-steel beams. In addition to that, the concrete slab-on-grade thickness was reduced by 125 mm. Also, the hybrid framework supporting typical floors, staircase, and upper roof was changed into a steel system (Figure 2). Despite the replacement of glulam sections in the new design, the mass of timber in the building still consists of 92%.

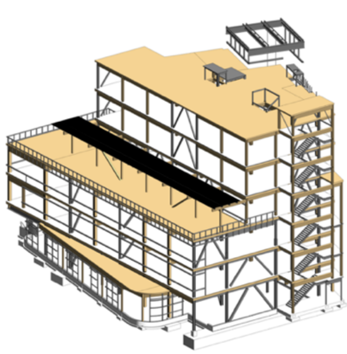

Figure 1: 3D Model - Design 1

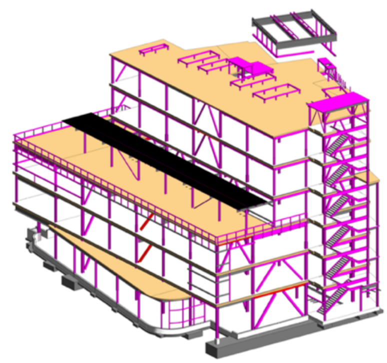

Figure 2: 3D Model - Design 2

3.2 Life Cycle Assessment

In this study, LCA will be applied to determine which structural design alternative produced lower environmental impacts throughout its life cycle. The LCA framework operates with four separate phases, goal and scope definition, inventory analysis, impact assessment, and interpretation. For this study, the same structure has been followed to implement the LCA in order to quantify the environmental impacts.

3.3 Goal and Scope Definition

The main scope of this study is to apply the LCA methodology to identify the environmental impacts of two different designs of the same building in Victoria, BC. The functional unit of this study is the environmental impact per 1 m2 of the engineering expansion building project that includes different percentages of structural elements over 60 years of life span. Figure 1 represents the initial design of the building, which consists of concrete, steel, and timber. The product system includes the foundation, concrete columns neck, slab-on-grade, the six floors, concrete cores, steel-wood stairs, glulam and PSL columns, W and HSS steel columns, braces of steel and wood, CLT floors (including concrete protective layer, excluding other finishes), walls, and roof were the main elements of investigation. As shown in Figure 2, the design alternative is composed of a foundation, concrete columns neck, slab-on-grade, the six floors, concrete cores, steel-wood stairs, W and HSS steel columns, braces of steel, CLT floors (including concrete protective layer, excluding other finishes), walls, and roof. The study was limited to the structural elements of both buildings, with all finishing components being excluded from the assessment. This decision was made to streamline the analysis and concentrate on core structural systems, which are critical to understanding the environmental impacts within the scope of this comparative study. The LCA system boundary was cradle-to-grave following EN 15978 standard, covering raw material acquisition, construction, building use (excluding B1, B3, B5, and B7), end-of-life, and beyond life (see Figure 3 for more details). This boundary ensures that no major life cycle phase is overlooked, providing a holistic perspective on carbon emissions, resource use, and waste generation.

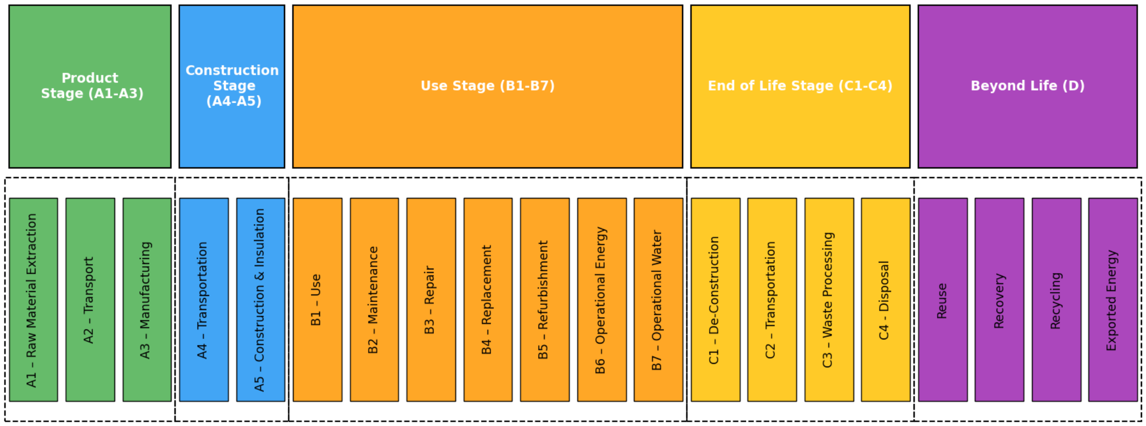

Figure 3: System boundary of LCA

3.4 Life Cycle Inventory

Life Cycle Inventory (LCI) analysis in the LCA involves the collection of data and modeling of the flows to, from, and within the product system, including resources or raw materials, energy by type, water, and emissions to air, water, and land by specific substance (Athena Sustainable Materials Institute n.d.). Athena has developed a set of regional North American life cycle inventory (LCI) datasets for key building materials, including concrete, steel, and wood, as around 90% to 95% of the structural and envelope components commonly used in commercial, institutional, light industrial, and residential buildings (Chen et al., 2020). To align with North American standards, such as those proposed by the City of Vancouver, the guidelines have been followed to conduct the LCA for this study (City of Vancouver, 2021). For this study, Athena Sustainable Materials Institute's Life Cycle Inventory (LCI) database was utilized to translate input flows into outputs, using Ecoinvent as a background database.

3.5 Life Cycle Impact Assessment

Life Cycle Impact Assessment (LCIA) is the process where the life cycle inventory's information is translated into the environmental impact scores. The aim of this process is to evaluate the extent to which various Flows- such as elementary, product, or waste- within a product system contribute to environmental impacts. Athena's Impact Estimator for Buildings (IE4B) was utilized for this purpose. The IE4B software employs the TRACI (Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts) LCIA. IE4B is an open free software tool that provides a cradle-to-grave life-cycle inventory (LCI), mostly developed for North American building industries, to estimate a whole building's environmental impacts (Chen et al., 2020). To implement the LCA in Athena, material quantity should be provided as an input. Therefore, the BIM model, drawings, and bill of materials prepared by the architect have been used for each design and their corresponding floor plans and elevations. The software then reported the footprints for different environmental impact categories such as global warming potential, acidification potential, human health particulate, ozone depletion potential, smog potential, fossil fuel consumption, and eutrophication potential.

4. INTERPRETATION OF RESULTS

4.1 LCA Measure of the Two Models

IE4B software was utilized after inputting the quantity of each design. Design 1 consists of 1,090 m³ of concrete, including foundation and slab on grade, 234.5 tonnes of steel for columns and beams, 183 tonnes of glulam timber for framework, 1829 m³ of CLT flooring, and 34 tonnes of galvanized studs. Similarly, these components were evaluated again to ensure accurate comparisons. For the updated design, the concrete volume was slightly reduced to 1040 m³. The primary difference between the two models lies in columns and beam elements, where the glulam timber was completely replaced by a steel frame using 365 tons of steel. Additionally, the CLT flooring thickness for each slab was increased by 2 mm, resulting in a total volume of 1870 m³. The walls and operational energy remained unchanged in both designs. The total environmental impacts of the ECSE building from cradle to grave are shown in Table 1. The results illustrate the environmental performance in terms of global warming, ozone depletion, acidification, Tropospheric ozone formation, eutrophication, and fossil fuel consumption while keeping design 1 as the reference design and design 2 as the proposed design.

Table 1: Comparative LCA measures from cradle to grave

Summary Measure	Unit	Reference Design Total Effects Cradle to Grave (Design 1)	Proposed Design Total Effects Cradle to Grave (Design 2)	% Difference
Global warming potential	kg CO_2 eq	4.44E+06	4.68E+06	5.13%
Stratospheric ozone depletion	kg CFC-11 eq	3.68E-01	3.66E-01	-0.34%
Acidification of land and water	kg SO_2 eq	1.66E+04	1.68E+04	1.32%
Eutrophication	kg N eq	3.79E+03	3.76E+03	-0.81%
Tropospheric ozone formation	kg O_3 eq	2.86E+05	2.88E+05	0.85%
Fossil Fuel Consumption	MJ	6.65E+07	6.71E+07	0.78%

Notably, the global warming potential for Design 2 is 5% higher than for Design 1. Although Design 2 has a mass of columns and beams and concrete of 50 tonnes and 50 m³ less compared to Design 1, the latter remains more environmentally sustainable. This is attributed to the incorporation of glulam timber in Design 1, which effectively stores CO_2 throughout its life cycle. Glulam timber demonstrates remarkable potential for carbon storage, making it a highly sustainable construction material. This capability arises from its ability to keep the carbon absorbed by trees during growth. This stored carbon remains locked within the timber until it decomposes or burns at the end of its life cycle (Dzhurko et al., 2024). Overall, Design 1 performs slightly better in terms of acidification of land and water, tropospheric ozone formation, and fossil fuel consumption. While Design 2 reduces concrete usage, improving its efficiency in areas like eutrophication and stratospheric ozone depletion. Furthermore, Design 2 was proposed due to field restrictions, such as the risk involved in leveraging a hybrid structure with an existing building. It is safer to use a more common scientifically accepted approach in such cases by obtaining steel frame sections for the connection. Additionally, Design 2 reduces project costs and avoids the need for highly experienced engineers, which would be necessary for more complex Design 1, especially in the given time constraints. Despite these adjustments, Design 2 still maintains a high standard, as it is certified as a net-zero building.

4.2 Carbon Footprint of Building Structure

A holistic analysis was conducted to illustrate the reason behind changing the design for each element throughout the whole life cycle stage. Figure 4 shows a breakdown of the carbon footprint associated with each assembly group of the ECSE building for the design alternatives. The analysis focused on the structural elements only. Firstly, the roof and floor elements are quite similar, with only a minor adjustment of 2 mm in the slab thickness, resulting in a 5% increase in carbon storage. The walls, both interior and exterior, remained unchanged for both designs. For the foundation, the designer was able to reduce the concrete volume required for Design 2 by 5%. The most notable difference between the two options lies in the beam and column elements. These components, which are made entirely of steel sections, are the primary contributors to the global warming potential (GWP) in Design 2. The results indicate a significant increase in GWP for Design 2 due to the addition of more steel frames compared to the glulam timber column sections used in Design 1. While Design 2 reduced 50 tonnes of column and beam sections, the structural framework for Design 1 still demonstrates a lower GWP because it relies mainly on glulam timber. This highlights the critical role of incorporating wood elements in structural design to achieve better environmental performance. Indeed, the difference between the two designs appears significant; however, Design 1 represents an ideal case with a highly efficient design. On the other hand, Design 2 remains a very sufficient option, particularly when viewed as a hybrid structure. Despite its higher GWP due to increased steel usage, Design 2 still achieves a level of efficiency that makes it a competitive alternative in certain contexts.

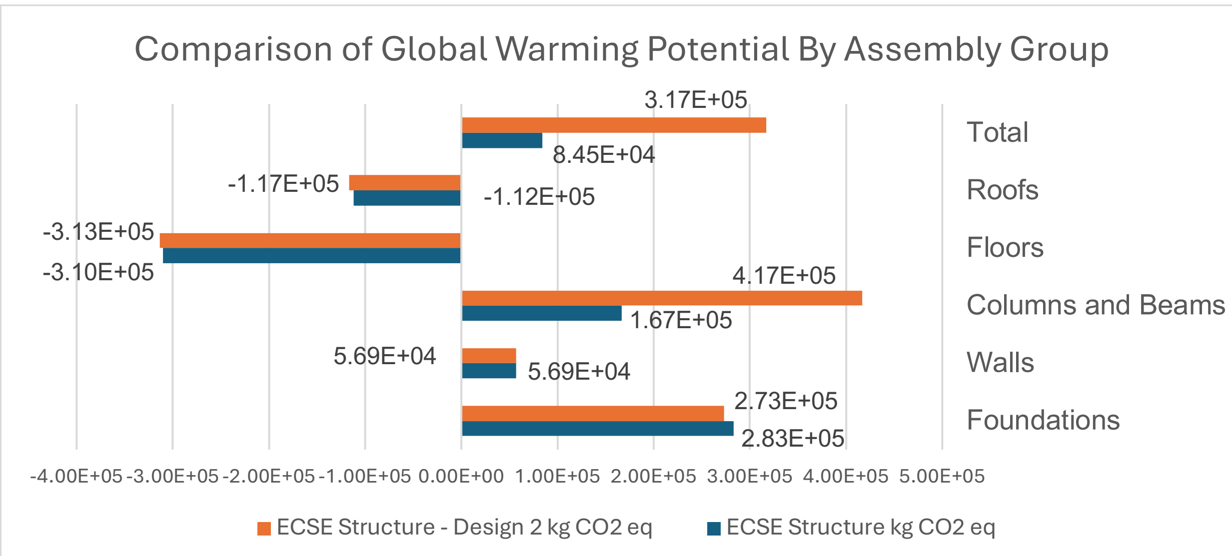

Figure 4: GWP by assembly group

Digging deeper into the comparison of the GWP, A Comparative analysis by the life cycle stage between each design was demonstrated in Figure 5. At the product stage (A1–A3), Design 1 emits 805,000 kg CO_2 eq compared to 841,000 kg CO_2 eq from Design 2. The reason behind this is that during the manufacturing phase, steel has the highest impact on emissions of carbon dioxide (Buchanan & Honey, 1994). Also, Design 1 uses more glulam timber material, which has a lower carbon footprint during manufacturing than the steel used predominantly in Design 2. In the construction phase (A4–A5), Design 2 has higher emissions at 118,000 kg CO_2 eq, while Design 1 emits 108,000 kg CO_2 eq. This difference is attributed to Design 2 due to the replacement of 183 tonnes of glulam timber, a low-carbon material used in Design 1, with 130 tonnes of steel, which has a much higher carbon footprint. Minor reduction in concrete volume and increment of CLT flooring thickness in Design 2 has a minimal impact compared to the added emissions of steel. In fact, since the size of the building and all the factors that would affect energy consumption remain unchanged across both designs, the operational energy is assumed to be of the same magnitude for both options. Therefore, any minor differences, such as those potentially arising from the different insulation efficiencies of timber and steel, were considered negligible. At the end-of-life stage (C1–C4), Design 2 performs slightly better, emitting 72,000 kg CO_2 eq compared to Design 1's 74,000 kg CO_2 eq, as Design 2 incorporates more steel, which has a lower environmental impact during disposal compared to timber mass (glulam columns). However, the most significant difference appears in building beyond life stage (D). Stage D measures the overall environmental benefits or burdens associated with material and energy flows that are reused, recycled, or recovered for energy purposes within the system boundary. This stage includes three distinct approaches, each based on different assumptions for calculating or defining the standards, in accordance with internationally accepted carbon footprint standards: PAS 2050, ISO 14067, and the WRI GHG Protocol for Products. According to the principles of these standards, if the forest is renewed after logging, the resulting forest growth contributes to the removal of carbon dioxide from the atmosphere, which is treated as a negative carbon emission (Chen et al., 2020). In this context, Design 1 achieves a GWP credit of -903,000 kg CO_2 eq, while Design 2 achieves -706,000 kg CO_2 eq. This indicates that Design 1 may offer greater potential for carbon recovery or reuse, likely due to its higher proportion of timber-based materials. When considering the total GWP across the whole life cycle stages, Design 1 results in 4,441,000 kg CO_2 eq, whereas Design 2 results in 4,682,000 kg CO_2 eq. This comparison indicates that Design 1 has a lower overall GWP. It is essential to consider these analyses from the perspective of environmental impact assessment and sustainable building practices, as such evaluations can play a crucial role in guiding material selection and design strategies that align with long-term climate goals.

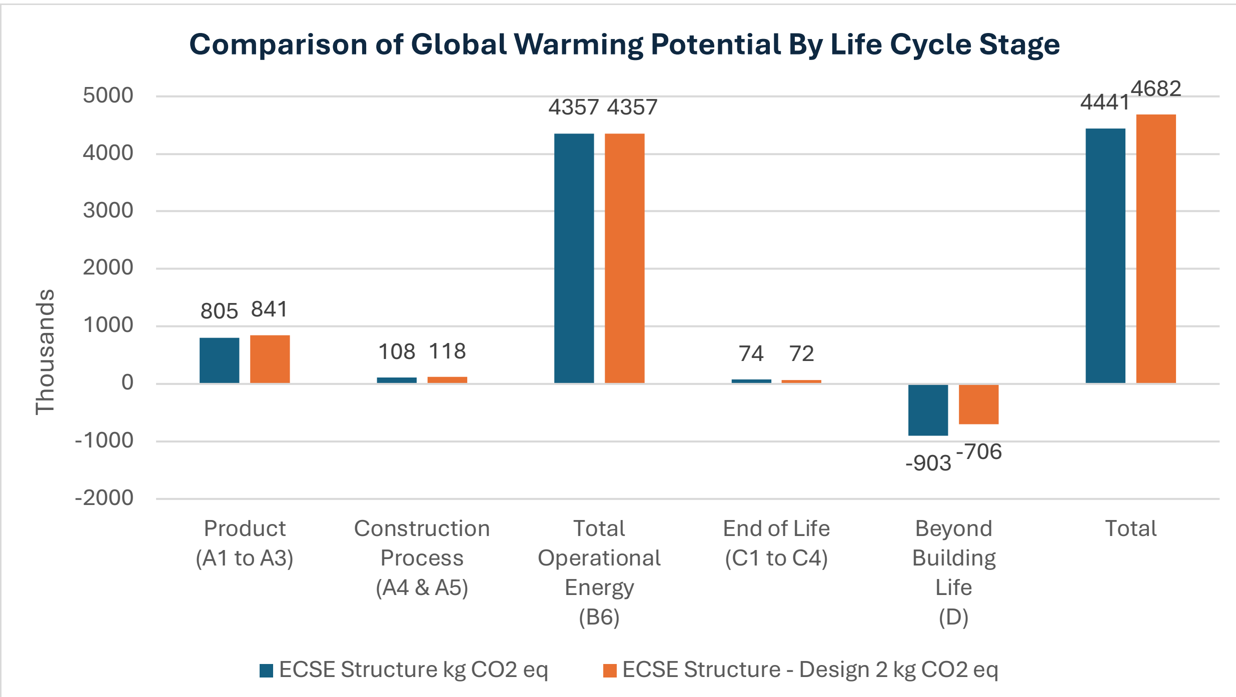

Figure 5: Comparison of global warming impacts over life-cycle stages A–D

5. CONCLUSIONS

This study introduced a comprehensive LCA comparison between two different structural designs for a building at the University of Victoria, Canada, using the Athena IE4B. The study focused on the environmental impacts of reducing the timber mass & increasing the proportion of steel within the structural framework, aiming to derive insightful knowledge in the area of LCA and define the impact of these changes on every stage of the life cycle. Specifically, the authors delved deeper into how minor changes in structural systems would affect the ecological system, which will aid planners, practitioners, decision-makers, and future studies to draw better attention to material contexts while optimizing hybrid structures. The analysis has demonstrated that the principal factor for achieving a better sustainable structure is not solely reducing the quantity of materials but also implementing a hybrid structural design. To be precise, a reduction of 14 % of columns and beams led to a higher global impact, even though more than 50 tonnes of materials were eliminated. Moreover, although Design 2 achieved a 5% reduction in concrete volume by removing the glulam columns and beams, the total carbon emissions remain higher than in the previous design. It was also revealed that the highest impact of Design 2 occurs during the construction phase, with a 9% increase compared to Design 1. These findings emphasize how reducing timber in the structure can significantly alter its environmental performance. In addition, the results highlight that the assumptions made in Stage D play a vital role in shaping how the overall carbon footprint influences decision-making. The 28% difference in GWP between the two design alternatives significantly impacts the overall reduction outcome. From a practical standpoint, Design 1 was proposed as an ideal sustainable option, offering a highly efficient solution with minimal emissions. However, in reality, several factors must be considered to design a more feasible choice. These include structural safety, building performance, constructability, project schedule and life cycle cost, and logistical challenges, such as the time and complexity of sourcing and shipping large quantities of glued and composite laminated timber. In this sense, Design 2 can be favorable for contractors as it has only steel sections of columns and beams while glulam sections were taken out which also crushes the project timeline and cost as well. On the other hand, Design 1, which is considered a greener option, has a higher mass, additional time to source timber columns and beams, higher cost, and performs worse in terms of fire. Hence, which design option is really more sustainable taking into consideration all of these aspects while making any decision? Is it the environmental performance that matters the most? Or the practical aspects could outweigh the ecological impacts? This sheds light on the importance of balancing sustainability with practical constraints. This question is highlighted here, but it will be addressed in detail in future studies that will direct the knowledge of the decision-making that is related to the LCA of this unique case study. The results build on previous literature concerning the environmental performance of structural elements. However, certain limitations may have influenced the assessment. The LCA tool used has restricted datasets and limited material options which might have affected reporting the environmental performance of the case study investigated in this paper.

ACKNOWLEDGMENTS

The authors would like to thank the entire team of engineers for their contribution in providing all the documents needed to conduct this study. Additionally, the authors acknowledge the financial support of the Natural Sciences and Engineering Research Council of Canada (NSERC) through Grant RGPIN-2020-04221, Transitions Towards Sustainable Construction.

REFERENCES

Ahbe, S., Braunschweig, A., & Müller-Wenk, R. (1990). Methodology for ecobalances based on ecological optimization. *Bern: Buwal (Safel).(Environment Series, 133)*.

Andersen, C. E., Rasmussen, F. N., Habert, G., & Birgisdóttir, H. (2021). Embodied GHG Emissions of Wooden Buildings—Challenges of Biogenic Carbon Accounting in Current LCA Methods. *Frontiers in Built Environment*, *7*, 729096. https://doi.org/10.3389/fbuil.2021.729096

Athena Sustainable Materials Institute. n.d. *LCA, LCI, LCIA, LCC: What's the Difference?* Accessed November 12, 2024. (Hauschild et al., 2018)

Buchanan, A. H., & Honey, B. G. (1994). Energy and carbon dioxide implications of building construction. *Energy and Buildings*, *20*(3), 205–217. https://doi.org/10.1016/0378-7788(94)90024-8

Bribián, I. Z., Capilla, A. V., & Usón, A. A. (2011). Life cycle assessment of building materials: Comparative analysis of energy and environmental impacts and evaluation of the eco-efficiency improvement potential. *Building and environment*, *46*(5), 1133-1140.

Bribián, I. Z., Usón, A. A., & Scarpellini, S. (2009). Life cycle assessment in buildings: State-of-the-art and simplified LCA methodology as a complement for building certification. *Building and environment*, *44*(12), 2510-2520.

Chen, Z., Gu, H., Bergman, R. D., & Liang, S. (2020). Comparative life-cycle assessment of a high-rise mass timber building with an equivalent reinforced concrete alternative using the Athena impact estimator for buildings. *Sustainability*, *12*(11), 4708.

Cordier, S., Robichaud, F., Blanchet, P., & Amor, B. (2021). Regional environmental life cycle consequences of material substitutions: The case of increasing wood structures for non-residential buildings. *Journal of Cleaner Production*, *328*, 129671.

City of Vancouver. (2021). *Embodied carbon guidelines*. City of Vancouver. https://vancouver.ca/files/cov/embodied-carbon-guidelines.pdf

Dzhurko, D., Haacke, B., Haberbosch, A., Köhne, L., König, N., Lode, F., Marx, A., Mühlnickel, L., Neunzig, N., Niemann, A., Polewka, H., Schmidtke, L., Von Der Groeben, P. L. M., Wagemann, K., Thoma, F., Bothe, C., & Churkina, G. (2024). Future buildings as carbon sinks: Comparative analysis of timber-based building typologies regarding their carbon emissions and storage. *Frontiers in Built Environment*, *10*, 1330105. https://doi.org/10.3389/fbuil.2024.1330105

Goedkoop, M. (2000). The eco-indicator 99 a damage-oriented method for life cycle impact assessment-*methodology* report, pre consultants. *http://www. pre-sustainability.com/content/reports*.

Guardigli, L., Monari, F., & Bragadin, M. A. (2011). Assessing Environmental Impact of Green Buildings through LCA Methods: Acomparison between Reinforced Concrete and Wood Structures in the European Context. *Procedia Engineering*, *21*, 1199–1206. https://doi.org/10.1016/j.proeng.2011.11.2131.

Guggemos, A. A., & Horvath, A. (2005). Comparison of Environmental Effects of Steel- and Concrete-Framed Buildings. *Journal of Infrastructure Systems*, *11*(2), 93–101. https://doi.org/10.1061/(ASCE)1076-0342(2005)11:2(93).

Hauschild, M. Z., Rosenbaum, R. K., & Olsen, S. I. (Eds.). (2018). *Life Cycle Assessment: Theory and Practice*. Springer International Publishing. https://doi.org/10.1007/978-3-319-56475-3

Hellweg, S., & Milà I Canals, L. (2014). Emerging approaches, challenges and opportunities in life cycle assessment. *Science*, *344*(6188), 1109–1113. https://doi.org/10.1126/science.1248361

Hunt, R. G., Sellers, J. D., & Franklin, W. E. (1992). Resource and environmental profile analysis: A life cycle environmental assessment for products and procedures. *Environmental Impact Assessment Review*, *12*(3), 245-269.Buchanan, A. H., & Honey, B. G. (1994a). Energy and carbon dioxide implications of building construction. *Energy and Buildings*, *20*(3), 205–217. https://doi.org/10.1016/0378-7788(94)90024-8.

Röck, M., Saade, M. R. M., Balouktsi, M., Rasmussen, F. N., Birgisdottir, H., Frischknecht, R., Habert, G., Lützkendorf, T., & Passer, A. (2020). Embodied GHG emissions of buildings – The hidden challenge for effective climate change mitigation. Applied Energy, 258, 114107. https://doi.org/10.1016/j.apenergy.2019.114107.

Teshnizi, Z., Pilon, A., Storey, S., Lopez, D., & Froese, T. M. (2018). Lessons Learned from Life Cycle Assessment and Life Cycle Costing of Two Residential Towers at the University of British Columbia. *Procedia CIRP*, *69*, 172–177. https://doi.org/10.1016/j.procir.2017.11.121

Treacy, M. (2020). La ecología política y el marxismo ecológico como enfoques críticos a la relación entre desarrollo económico y medio ambiente. *Revista colombiana de sociología*, *43*(2), 241-266.