Case Studies on the Life Cycle Assessment of Lumber Production and of Tall Wood Buildings

by

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Abstract

Mass timber provides a low-carbon alternative to steel and concrete, reducing global warming potential (GWP) and non-renewable energy use while acting as a carbon sink. Life cycle assessment (LCA) evaluates environmental impacts, supporting sustainable construction practices. This research includes three LCA case studies. The first examined softwood lumber production in New Brunswick, Canada, with emissions of 43 kg CO_2 eq/m^3, relying on 58% renewable energy from woody biomass during kiln drying. The second analyzed hardwood lumber, emitting 41 kg CO_2 eq/m^3 up to sawing, using 98% non-renewable grid energy. Both softwood and hardwood offset their emissions with stored carbon, achieving negative GWP. The third study compared cradle-to-grave impacts of hybrid mass timber-steel, full mass timber, steel, and concrete designs in the Bakers Place project, USA. Mass timber significantly reduced GWP and non-renewable energy but showed higher acidification and eutrophication impacts due to transportation and landfill decomposition.

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List of Symbols, Nomenclature, or Abbreviations

LCA: Life Cycle Assessment

LCI: Life Cycle Inventory

LCIA: Life Cycle Impact Assessment

LEED: Leadership in Energy and Environmental Design

EWP: Engineered Wood Products

OSB: Oriented Strand Board

LVL: Laminated Veneer Lumber

MTP: Mass Timber Product

CLT: Cross Laminated Timber

GLT: Glue Laminated Timber

GHG: Green House Gas

TRACI: Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts

ODP: Ozone Depletion Potential

GWP: Global Warming Potential

AP: Acidification Potential

EP: Eutrophication Potential

SP: Smog Potential

NB: New Brunswick

WI: Wisconsin

psf: pounds per square foot

eq (Following CO_2, SO_2, O_3, N, and CFC-11): Equivalent

1 Introduction

1.1 Background

1.1.1 Climate Change

The rapid increase in greenhouse gas (GHG) emissions, such as carbon dioxide and methane, significantly intensifies the greenhouse effect, trapping more heat in the Earth's atmosphere and driving global temperature rise. This process, known as global warming potential (GWP), is a critical factor in climate change. The Intergovernmental Panel on Climate Change (IPCC) warns that exceeding a 2°C rise in temperature could lead to irreversible environmental damage. Current projections indicate that global temperatures could rise by 3.5°C by the end of the century if GHG emissions continue at the current pace (IPCC, 2021). Canada, in particular, is experiencing warming at twice the global average, with northern regions heating nearly three times faster than the rest of the world (Environment and Climate Change Canada, 2024). This rapid warming already has tangible effects, as seen through increasing instances of natural disasters both in Canada and globally (Bush & Lemmen, 2019). These examples include wildfire (Kulkarni, 2021) and flooding events (Kotyk, 2021) in the province of British Columbia in 2021 and flooding in the province of Manitoba in 2022 (Wildes, 2022). Even New Brunswick had a flooding event in 2019 (Ferreras, 2019). In Canada, the 2016 Fort McMurray wildfire forced the evacuation of more than 88,000 people, caused the destruction of around 2,400 homes and buildings, and resulted in economic losses estimated at $9.9 billion (Mamuji & Rozdilsky, 2019). Similarly, the 2013 Alberta floods caused widespread damage, displacing 100,000 residents and incurring over $1.7 billion in insured losses (Clague et al., 2010). In the United States, Hurricane Harvey in 2017 ranked among the costliest natural disasters, with

damages amounting to $125 billion and 68 direct fatalities (Smith, 2020). Hurricane Katrina in 2005 was even more devastating, claiming over 1,800 lives and causing approximately $125 billion in damages (Clague et al., 2010). The increasing frequency of such events underscores the urgent need for comprehensive climate action to mitigate these profound impacts. In 2015, Canada, alongside 194 other nations, committed to the Paris Agreement, aiming to limit global temperature rise to well below 2°C, with an ideal target of 1.5°C (Government of Canada, n.d.). Understanding and accurately estimating GHG emissions is crucial for developing effective strategies to mitigate climate change and avoid catastrophic impacts.

1.1.2 Building and Wood Materials

The building industry is a significant contributor to GHG emissions and consumes a large amount of natural resources arising from all stages, with direct energy needs including operational energy and indirect needs, including the energy necessary for the production and installation of building materials, referred to as embodied carbon (Sartori & Hestnes, 2007). According to Architecture 2030, buildings are responsible for 42% of global CO_2 emissions, with 15% of embodied carbon attributed to structural materials and 27% to building operations (Architecture 2030, n.d.). As global construction activities continue to rise, many countries are increasingly committed to achieving the United Nations' sustainable development goals by reducing the environmental impact of the construction sector, leading to a growing interest in materials with lower environmental footprints.

Wood is a natural, renewable, reusable, and recyclable resource that can play a critical role in reducing negative impacts on the climate and environment when sourced from sustainably managed forests (Gong, 2022). A common approach to utilize forests to mitigate climate change is significant carbon storage in wood products (Perez-Garcia et al. 2007). Wood products can act as carbon sinks since trees can absorb and store carbon dioxide through photosynthesis (Organschi et al., 2016). However, this carbon is released back into the atmosphere after the trees start to decay. One effective way to maintain the carbon stored in trees for the long term is to harvest them for wood products before they decompose, allowing newly planted trees to take their place. In managed forests, this cycle of replacing harvested trees ensures that carbon accumulation continues in the new growth while the carbon from previous generations is stored in wood products, enhancing the total carbon sequestration over time. Some commonly known wood products include fuel woods, pulp and paper, lumber, plywood, wooden crafts, wood-based furniture, and wood-based structural materials for buildings such as panels and boards with a lifespan of 50 to 100 years, that can delay the release of sequestered carbon into the atmosphere due to their longer service life compared with the other wood products. The unique feature of Carbon storage of wood does not occur in other structural materials, such as steel and concrete, allowing us to transform our built environment into carbon sinks instead of sources. Moreover, mass timber products (MTPs) is a defined category of engineered wood products (EWPs), including cross-laminated timber (CLT), glued laminated timber (glulam), nail-laminated timber, and dowel-laminated timber (Gong, 2019), which enables the construction of mid- and high-rise buildings with wood as an alternative to structural

steel and reinforced concrete (Harte, 2017). However, the environmental benefits of wood-based products must be appropriately quantified using relevant tools (Kutnar & Hill, 2017).

1.1.3 LCA and Carbon Policies

Life cycle assessment (LCA) is an internationally recognized, science-based method used to assess the environmental impact of products or services by measuring the energy and materials used and emissions released during each life cycle stage. The functional unit is defined as the quantity of the identified function of the product, for example, the production of $1m^3$ of wood or 1 m^2 of building area. For LCA studies that involve comparisons, choices of functional units are especially important (International Organization for Standardization, 2006a). LCA studies can either evaluate the entire product life cycle, commonly known as "cradle-to-grave or cradle-to-cradle" or focus on specific stages such as "cradle-to-gate" or "gate-to-gate (Puettmann et al., 2021). The LCA process involves four major steps: defining the goal and scope, developing a life-cycle inventory (LCI), performing a life-cycle impact assessment (LCIA), and interpreting the results (International Organization for Standardization, 2006b).

Multiple studies using LCA showed that the application of MTPs in construction could reduce the GWP of buildings (Teshnizi et al., 2018; Pierobon, et al., 2019; Skullestad et al., 2016; Liang et al., 2020; Chen et al., 2020). In 2021, Canada committed to reducing emissions by 40-45% below 2005 levels by 2030 (Environment and Climate Change Canada, 2021), aiming for net-zero emissions by 2050 (Government of Canada, 2021). As part of this effort, the federal government introduced Green Procurement, requiring the disclosure of embodied carbon in construction materials and mandating LCAs by 2025,

with a goal to cut embodied carbon by 30% in major projects starting in 2025 through recycled materials and performance-based design. In July 2024, Canada strengthened its Green Building Strategy to further address GHG emissions in the construction sector. This update mandates the use of low-carbon materials and requires Environmental Product Declarations (EPDs) to disclose their environmental impact. While the current focus is on concrete, the policy will eventually expand to include materials like steel and wood, aligning with similar U.S. policies (Natural Resources Canada, n.d.-a). EPDs of building products play a crucial role in the design of buildings to achieve green certifications. Products with validated EPDs are eligible for gaining credits from the Leadership in Energy and Environmental Design (LEED), Green Globes, and other green building rating systems, which can also be used to demonstrate compliance with other green building regulations. The strategy also emphasizes improving material performance and reducing embodied carbon throughout the building lifecycle assessment (Natural Resources Canada, n.d.-a). In the case of LEED, the building designers would use the LCA to show that the building has at least 10% reduced environmental impact in at least two impact categories compared to a baseline level to receive 3 credits (Al-Ghamdi & Bilec, 2017). Supporting these efforts, the NRC's LCA squared initiative is developing a comprehensive national LCI database for construction materials, providing critical data for accurate LCAs (Natural Resources Canada, n.d.-b). Together, these measures aim to significantly reduce embodied carbon and advance sustainable construction practices across Canada. Additionally, the New Brunswick Climate Change Action Plan, launched in December 2016, promotes sustainability in various sectors, including construction. It outlines 118 actions, with two key strategies focusing on wood. Action Plan 21 integrates wood products with favorable

life cycle evaluations, while Action Plan 61 promotes wood as a renewable construction material through building codes and standards (Government of New Brunswick, 2022). This reflects a robust commitment to addressing climate change at both national and provincial levels.

1.2 Objectives and Scope of Research

This research was aimed at applying LCA to conduct three distinct case studies to address climate change: Cradle-to-Gate LCA of softwood and hardwood lumber production and Cradle-to-Grave LCA of a tall mass timber hybrid building. To reach this, the following activities were performed.

Case studies 1, 2) Cradle-to-Gate LCA on Lumber Production

This part includes two case studies that addressed New Brunswick's emission reduction targets by analyzing the Cradle-to-Gate life cycle stages of lumber products, including one softwood and two hardwood sawmills in New Brunswick (NB). The specific objective of the first case study was to collect the data to create the LCI, then via SimaPro, create a LCA report, emphasizing various impact categories, especially GWP. The report tracked the carbon footprint from harvesting and transportation to the manufacturing stages of lumber. Impact values for each unit process were highlighted, and the values were presented per 1 m^3 of lumber as the functional unit. Additionally, the results were compared with an earlier LCA report that covered lumber facilities in Eastern Canada (Athena Sustainable Materials Institute, 2018).

Case study 3) Cradle-to-grave LCA on a Mass Timber- steel hybrid Building

The ongoing Bakers Place project, a 14-story mass timber-steel hybrid construction in Madison, WI, USA, serves as a real-life case study for sustainable building in North America with passive house principles, LEED certification, and green building concepts. The specific objective of the second case study was to, via Tally® LCA tool, compare the baseline scheme of hybrid design to the three functional equivalent alternative designs using full mass timber, full steel, and post-tensioned concrete as the structural framing materials. The results provided a comparison of the whole building impact categories expressed per 1 m^2 of the four structural designs as the functional unit.

1.3 Organization of Thesis

The content of this thesis is organized as six (6) chapters.

Chapter 1: The background on the issue of climate change and the strategies used to address it, outlines the objectives and scope of the work, and details the organization of the study.
Chapter 2: Literature review on LCA, lumber production, MTPs and the application of LCA in evaluating the environmental performance of mass timber buildings.

Chapter 3: Investigate the environmental impacts of the softwood lumber production in NB by conducting a cradle-to-gate LCA study.

Chapter 4: Investigate the environmental impacts of the hardwood lumber production in NB by conducting a cradle-to-gate LCA study.

Chapter 5: Investigate the environmental impacts of the Bakers Place mass timber- steel hybrid building in Madison, WI, USA by conducting a cradle-to-grave LCA study and compare the result with the alternative concrete, steel and full mass timber structural design.

Chapter 6: General conclusions and recommendations.

References

Al-Ghamdi, S. G., & Bilec, M. M. (2017). Green building rating systems and whole-building life cycle assessment: Comparative study of the existing assessment tools. Journal of Architectural Engineering, 23(1), 04016015. https://doi.org/10.1061/(asce)ae.1943-5568.0000222

Architecture 2030. (n.d.). Why the built environment? Retrieved July 15, 2024, from https://www.architecture2030.org/why-the-built-environment/

Athena Sustainable Materials Institute. (2018). A Cradle-to-Gate Life Cycle Assessment of Eastern Canadian Surfaced Dry Softwood Lumber. https://www.athenasmi.org/wp-content/uploads/2018/07/CtG-LCA-of-Eastern-Canadian-Surfaced-Dry-Softwood-Lumber.pdf.

Bush, E., & Lemmen, D. S. (Eds.). (2019). Canada's changing climate report. Government of Canada. Retrieved May 24, 2024, from https://changingclimate.ca/site/assets/uploads/sites/2/2020/12/CCCR_FULLREPORT-EN-FINAL.pdf

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 (Switzerland), 12(11). https://doi.org/10.3390/su12114708

Environment and Climate Change Canada. (2021). Canada's enhanced nationally determined contribution: Backgrounder. Ottawa, Canada. Retrieved July 10, 2024, from https://www.canada.ca/en/environment-climate-change/news/2021/04/canadas-enhanced-nationally-determined-contribution.html

Environment and Climate Change Canada. (2024). Temperature change in Canada. Retrieved November 6, 2024, from https://www.canada.ca/content/dam/eccc/documents/pdf/cesindicators/temperature-change/2024/temperature-change-en.pdf

Gong, M. (2019). Lumber-based mass timber products in construction. In Engineered wood products for construction. IntechOpen. https://doi.org/10.5772/intechopen.85808

Gong, M. (Ed.). (2022). Engineered wood products for construction. IntechOpen. https://doi.org/10.5772/intechopen.92960

Government of Canada. (n.d. a). Greenhouse gas emissions: Drivers and impacts. Environment and Climate Change Canada. Retrieved August 10, 2024, from https://www.canada.ca/en/environment-climate-change/services/environmental-indicators/greenhouse-gas-emissions-drivers-impacts.html

Government of Canada. (2021). Canadian Net-Zero Emissions Accountability Act, S.C. 2021, c. 22. Retrieved September 12, 2024, from https://laws-lois.justice.gc.ca/eng/acts/c-19.3/FullText.html

Government of New Brunswick. (2022). New Brunswick's Climate Change Action Plan 2022-2027: Our Pathway Towards Decarbonization and Climate Resilience. Fredericton, NB: Government of New Brunswick. https://www.gnb.ca/climatechangeactionplan

Harte, A. M. (2017). Mass timber – the emergence of a modern construction material. Journal of Structural Integrity and Maintenance, 2(3), 121–132. https://doi.org/10.1080/24705314.2017.1354156

International Organization for Standardization. (2006a). Environmental management—Life cycle assessment—Principles and framework (ISO Standard No. 14040:2006). https://www.iso.org/standard/37456.html

International Organization for Standardization. (2006b). Environmental management—Life cycle assessment—Requirements and guidelines (ISO Standard No. 14044:2006). https://www.iso.org/standard/38498.html

Intergovernmental Panel on Climate Change. (2021). Climate change 2021: The physical science basis. Working Group I contribution to the IPCC Sixth Assessment Report. Cambridge University Press. https://www.ipcc.ch/assessment-report/ar6

Kutnar, A., & Hill, C. (2017). Life cycle assessment–opportunities for forest products sector. BioProducts Business, 2(6), 52-64. https://biobus.swst.org/index.php/bpbj/article/view/10

Liang, S., Gu, H., Bergman, R., & Kelley, S. S. (2020). Comparative life-cycle assessment of a mass timber building and concrete alternative. Wood and Fiber Science, 52(2), 217–229. https://doi.org/10.22382/wfs-2020-019

Mamuji, A., & Rozdilsky, J. L. (2019). The Fort McMurray wildfires: A case study in disaster management. Canadian Public Administration, 62(3), 396-421. https://doi.org/10.1111/capa.12323

Clague, J. J., & Bobrowsky, P. T. (2010). Natural hazards in Canada. Geoscience Canada, 37(1), 17-33. https://doi.org/10.12789/geocanj.2010.37.003

Natural Resources Canada. (n.d.-a). The Canada Green Buildings Strategy: Transforming Canada's buildings sector for net-zero. Retrieved August 15, 2024, from https://natural-resources.canada.ca/transparency/reporting-and-accountability/plans-and-performance-reports/departmental-strategies/the-canada-green-buildings-strategy-transforming-canadas-buildings-sector-for-net-zer/26065

National Research Council Canada. (n.d.-b). Low Carbon Assets through Life Cycle Assessment initiative. Retrieved August 15, 2024, from https://nrc.canada.ca/en/research-development/research-collaboration/programs/low-carbon-assets-through-life-cycle-assessment-initiative

Organschi, A., Ruff, A., Oliver, C. D., Carbone, C., & Herrmann, E. (2016, August 22-25). Timber city: Growing an urban carbon sink with glue, screws, and cellulose fiber. In Proceedings of the World Conference on Timber Engineering (WCTE 2016), Vienna, Austria.

https://www.researchgate.net/publication/305779832_Timber_City_Growing_an_Urban_Carbon_Sink_with_Glue_Screws_and_Cellulose_Fiber

Perez-Garcia, J., Lippke, B., Comnick, J., & Manriquez, C. (2007). An assessment of carbon pools, storage, and wood products market substitution using life-cycle analysis results. Wood and Fiber Science, 37, 140–148.

Pierobon, F., Huang, M., Simonen, K., & Ganguly, I. (2019). Environmental benefits of using hybrid CLT structure in midrise non-residential construction: An LCA based comparative case study in the U.S. Pacific Northwest. Journal of Building Engineering, 26 (February). https://doi.org/10.1016/j.jobe.2019.100862

Puettmann, M., Pierobon, F., Ganguly, I., Gu, H., Chen, C., Liang, S., Jones, S., Maples, I., & Wishnie, M. (2021). Comparative LCAs of Conventional and Mass Timber Buildings in Regions with Potential for Mass Timber Penetration. Sustainability, 13(24), 13987. https://doi.org/10.3390/su132413987

Sartori, I., & Hestnes, A. G. (2007). Energy use in the life cycle of conventional and low-energy buildings: A review article. Energy and Buildings, 39(3), 249–257. https://doi.org/10.1016/j.enbuild.2006.07.001

Skullestad, J. L., Bohne, R. A., & Lohne, J. (2016). High-rise timber buildings as a climate change mitigation measure - A comparative LCA of structural system alternatives. Energy Procedia, 96(1876), 112–123. https://doi.org/10.1016/j.egypro.2016.09.112

Smith, A. B. (2020). U.S. billion-dollar weather and climate disasters, 1980–2020. NOAA National Centers for Environmental Information. Retrieved 12 October, 2024, from https://www.ncdc.noaa.gov

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(May), 172–177.

2 Literature Review

2.1 Life Cycle Assessment (LCA) and commonly used software programs

The purpose of LCA is to evaluate the environmental impacts of a product throughout its entire life cycle. Every product requires energy for production, and many also involve energy-intensive processes before reaching consumers. Each phase of a product's lifecycle—manufacturing, transport, usage, maintenance, and disposal—demands energy and can lead to a range of emissions, each having distinct environmental impacts. These stages are interconnected, as the outputs from one process are inputs for another, creating a complex chain of dependencies. The environmental impacts from one stage carry over to the next as the product progresses through its lifecycle. This interconnected system forms the core principle of LCA, which takes a holistic view of environmental impacts across a product's life cycle. The International Organization for Standardization defines the life cycle as "consecutive and interlinked stages of a product system, from the raw material acquisition or generation from natural resources to final disposal" in the context of LCA (International Organization for Standardization, 2006a). The concept of Life Cycle Assessment (LCA) traces its origins to early explorations in life cycle thinking, which emerged from real-world challenges in product design and environmental responsibility. One notable example dates back to 1969 when Coca-Cola sought to determine whether glass or plastic containers had a smaller environmental footprint. Similarly, in the 1990s, heated debates arose over whether paper or plastic bags were the greener choice. These early studies highlighted the complexity of environmental impact assessment, revealing that the answer was not straightforward. Factors like material sourcing, energy consumption, and the entire life cycle of a product influence its overall environmental

performance. These explorations underscored that making eco-friendly choices requires a deeper dive into data and analysis—there are no one-size-fits-all answers. The shift in thinking laid the foundation for modern LCA methodologies, which provide a comprehensive approach to evaluating the environmental impacts of products and services. From resource extraction to disposal, LCA focuses on energy use, resource consumption, and emissions, offering a holistic view that supports more informed and sustainable decision-making (Matthews et al., 2014). In today's setting, LCA is widely utilized to assess not just products but whole sectors, with uses that reach into the construction materials and building industries. Standardization of LCA started in the 1990s with the publication of multiple LCA guides and handbooks. The involvement of the International Organization of Standardization (ISO) in the field of LCA began in 1994 when they adopted the formal task of standardization of methods and procedures of LCA (Guinée et al., 2011). The ISO LCA Standard is globally recognized and consists of two key documents: ISO 14040:2006, which outlines the principles and framework, and ISO 14044:2006, which provides the requirements and guidelines. The standard was first introduced in 1997 and last updated in 2006. ISO 14040 is aimed at managers, while ISO 14044 is more practical, guiding LCA practitioners in implementing life cycle thinking for decision-making (Matthews et al., 2014).

According to ISO 14044 (International Organization for Standardization, 2006b), a complete LCA study needs to include four phases, which include: Goal and scope definition, life-cycle inventory (LCI) analysis, life-cycle impact assessment (LCIA), and interpretation. In Figure 2-1, the relationship between these four phases is demonstrated.

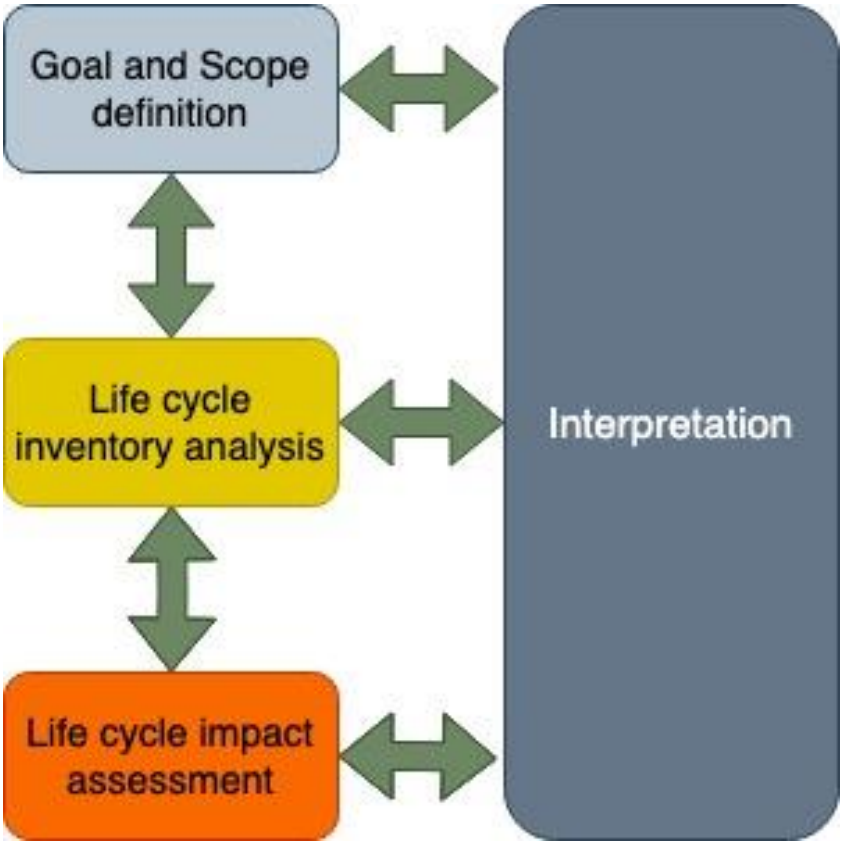


Figure 2-1: LCA framework as described in ISO 14040 (International Organization for Standardization, 2006a).

Phase 1: Goal and Scope

Defining the goal and scope of an LCA study involves specifying the function, functional unit, system boundaries, level of detail, assumptions, limitations, and intended use of the results. The goal defines the study's purpose, while the scope determines which life cycle stages will be analyzed. The system boundary identifies the stages or processes included in the assessment, which are directly influenced by the goal and scope. LCA studies are generally categorized as cradle-to-gate, gate-to-gate, or cradle-to-grave. For instance, Milota (2015) conducted a gate-to-gate LCA of softwood lumber production, covering the process from log delivery to dry lumber output but excluding forestry and disposal stages. In contrast, Puettmann & Wilson (2007) performed a cradle-to-gate LCA that spanned from forest regeneration to product transportation to the building site.

When conducting LCA on buildings, researchers can use well-defined modules defined in EN 15978:2011: sustainability of construction works, assessment of the environmental performance of buildings, and calculation method (Figure 2-2) (European Committee for Standardization, 2011). The boundary covering modules A1 to A4 is called cradle-to-gate, which tracks a product's life cycle from raw material extraction to when it leaves the factory. Expanding this to include all stages from A1 to C4, covering the product's entire life span—from production to use and disposal—is called cradle-to-grave. If module D is included, which accounts for the benefits and impacts beyond the system boundary, it's referred to as cradle-to-cradle.

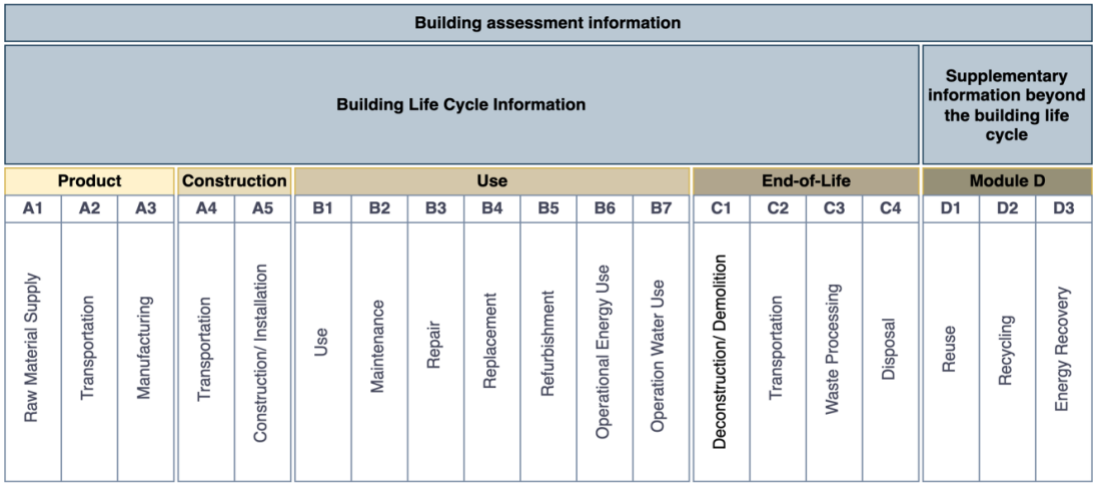


Figure 2-2: Life cycle stages adapted from EN 15978:2011 (European Committee for Standardization, 2011).

Phase 2: Life Cycle Inventory Analysis

Conducting a Life Cycle Inventory (LCI) analysis involves gathering data on the system's inputs and outputs, which can come from primary or secondary sources. Primary data is collected firsthand through surveys, observations, or properties' measurements tailored to the study's context. For example, this might include measuring the electricity or water used at a production facility. However, many LCA studies rely on secondary data to save time and resources. Secondary data comes from previous research or dedicated LCA databases. In North America, commonly used databases include the U.S. Life Cycle Inventory (USLCI), developed by the National Renewable Energy Laboratory (NREL), and the Athena database. The USLCI offers detailed data on energy and material flows for various products, while the Athena database provides extensive information on construction materials, including energy use, transportation, and demolition. Another widely used resource, especially in Europe, is the Ecoinvent database, which offers comprehensive LCI data. Collecting and analyzing this data is a critical step in the LCI process, providing the foundation for assessing environmental impacts in an LCA study.

Phase 3: Life Cycle Impact Assessment

Life Cycle Impact Assessment (LCIA) translates the inventory of material and energy flows into measurable environmental impacts (Hauschild & Huijbregts, 2015). Key factors influencing LCIA results include the system boundaries, the functional unit, and the specific methods used. These elements are crucial when comparing two LCA studies, as they determine whether the comparison is valid and meaningful (Athena Sustainable Materials Institute, 2018). Understanding these variables ensures that the findings from different studies can be accurately interpreted and applied in decision-making.

In North America, the Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI), developed by the U.S. Environmental Protection Agency (EPA), is widely used to assess several environmental impact categories (Bare, 2011). These categories include Ozone Depletion Potential (ODP), Global Warming Potential (GWP), Acidification Potential (AP), Eutrophication Potential (EP), Smog Formation Potential (SP), and energy consumption (Bare, 2011). Each impact is calculated using scientifically derived conversion factors known as characterization factors (Curran, 2006; Solomon et al., 2007; Stocker et al., 2013). For instance, GWP is typically expressed as "CO_2 equivalent" (CO_2 eq), as CO_2 is used as the reference gas. This means that other substances are converted to an equivalent amount of CO_2 based on their warming effect. For example, 1 kg of methane has a GWP of 25, meaning it has 25 times the warming potential of 1 kg of CO_2. Understanding these expressions is crucial for interpreting LCA results. Table 2-1 summarizes key impact categories and their corresponding units of measurement.

Table 2-1: Common life cycle impact categories and units.

Impact Category	Unit
Global Warming	kg CO_2 equivalent
Acidification	kg SO_2 equivalent
Smog	kg O_3 equivalent
Eutrophication	kg N equivalent
Ozone Depletion	kg CFC-11 equivalent

Phase 4: Life cycle Interpretation

Life cycle interpretation involves identifying key issues and evaluating the results of an LCA study. This phase focuses on interpreting data from the LCI analysis and the LCIA (Sharma et al., 2011). The goal is to derive essential conclusions from the findings and, in some cases, provide recommendations to address the objectives set in the initial phase of the study. This step ensures that the results are aligned with the study's purpose and can inform decision-making.

Using specialized software tools greatly facilitates conducting LCA (Pechenart & Roquesalane, 2014). Selecting the right LCA software is crucial and mainly depends on the project's scope or objectives (Ormazabal et al., 2014). Notable LCA tools include Sphera and OpenLCA, both from Germany, and SimaPro, developed by the Netherlands-based company PRé Consultants. Many studies rely on these tools for global product evaluations, and SimaPro is a popular choice because of its comprehensive database. SimaPro comes with the Ecoinvent and US LCI databases, giving users extensive access to LCI datasets (Sahoo et al., 2019). However, SimaPro is not free, which makes it less accessible compared to OpenLCA, an open-source option where users must purchase LCI databases separately (Gu, 2022).

SimaPro is particularly prevalent in North America for conducting CORRIM-initiated LCAs on major wood products such as softwood lumber (Milota et al., 2005), softwood plywood (Wilson & Sakimoto, 2005), I-joists (Wilson & Dancer, 2005a), glue-laminated timber (Puettmann & Wilson, 2005), and laminated veneer lumber (Wilson & Dancer, 2005b). Additionally, SimaPro can be utilized for both product-level and building-level LCA studies, making it a versatile tool. Other common LCA tools for whole-building

assessments include Athena Impact Estimator, Tally® LCA, and OneClick LCA. Athena Impact Estimator, developed by the Athena Sustainable Materials Institute in Canada, uses a regionally sensitive database. It needs full coverage for specific areas in North America and allows users to adjust its LCI content. Tally® LCA, developed by Kieran Timberlake Innovations in collaboration with Autodesk and PE International in the USA, integrates seamlessly with Autodesk Revit, simplifying the LCA process. However, it requires utilizing the Revit platform and limits the ability to modify its LCI database or LCIA methods (Gu, 2022). Finally, OneClick LCA, originating from Finland and with extensive global utilization, has emerged as a pivotal LCA tool for conducting comprehensive LCA at the building level. Table 2-2 summarizes the different aspects of the common LCA software.

Table 2-2: Characteristics of the selected software tools for LCA.

Software	Scope of LCA	Database	Cost	Data adjustment	Limitations
SimaPro	Product and building	EcoInvent, U.S. LCI, DataSmart, and others	Not free	Yes, for region-specific studies in North America, Europe, and other supported regions.	1. Need to add details, such as end of life information, manually if they are not included in the database. 2. Material identification difficulty
Sphera (Gabi)	Product and building LCA	GaBi-4500 datasets, ecoinvent, U.S. LCA (NREL)	Not free	Yes, for region-specific studies in North America, Europe, and other supported regions.	Dataset Integration Challenges
Open LCA	Product and building LCA	No, need to be purchased	Free and open source	Yes, for region-specific studies globally, based on the purchased database (e.g., Europe, North America).	Limited integrated data availability
Athena Impact Estimator	Building LCA	Athena LCI database (regional)	Free	Cannot adjust data for regions not included in North American-focused database.	Limited Regional Adaptability

Table 2-3: Characteristics of the selected software tools for LCA. (continued)

Software	Scope of LCA	Database	Cost	Data adjustment	Limitations
Tally	Building LCA	Sphera (Gabi), (limited customizability)	Not free	Cannot adjust data for regions not included in North American-focused database.	1. Limited Scope for Non-Building Projects 2.Data Gaps 3.Limited Customization
One Click LCA	Product and building LCA	Various regional databases, Ecoinvent, others	Not free	Yes, highly customizable for region-specific studies in North America, Europe, and other supported regions globally.	1.less suitable for product-level 2.Limited Customization

Studies comparing the results of different LCA software have consistently shown variations, mainly due to various databases and methodologies used for impact assessment (Ormazabal et al., 2014). Silva et al. (2017) examined the production of particleboards in Brazil using multiple LCA software tools, including Sphera, openLCA, SimaPro, and Umberto, to compare their outputs. According to the study, SimaPro calculated higher impacts for acidification and photochemical ozone formation compared to other tools due to variations in impact factors within each software's database (Silva et al., 2017). Moreover, Gu et al. (2024) compared two widely used LCA software tools, SimaPro and Athena Impact Estimator, by assessing the environmental impacts of a traditional institutional building and a mass timber building. While both tools produced similar conclusions for GWP during stages A1 to A3, they reported significantly different numerical values for other impact categories, such as ozone depletion and eutrophication. Differences in their LCI databases caused these variations, showing the importance of using the same software and database for consistent and fair comparisons in LCA studies (Gu et al., 2024).

2.2 LCA on the Building Sector

The potential for impacts due to climate change has drawn the attention of many industry sectors. The building sector is energy- and carbon-intensive, which has significant potential for reducing GHG emissions (Fnais et al., 2022). The building sector consumes significant resources, accounts for about 30% of world energy use (Berardi, 2017) and produces 42% of CO_2 emissions, including operational and embodied carbon annually

(Architecture 2030, n.d). Figure 2-3 shows the contribution of each sector to annual CO_2 emissions.

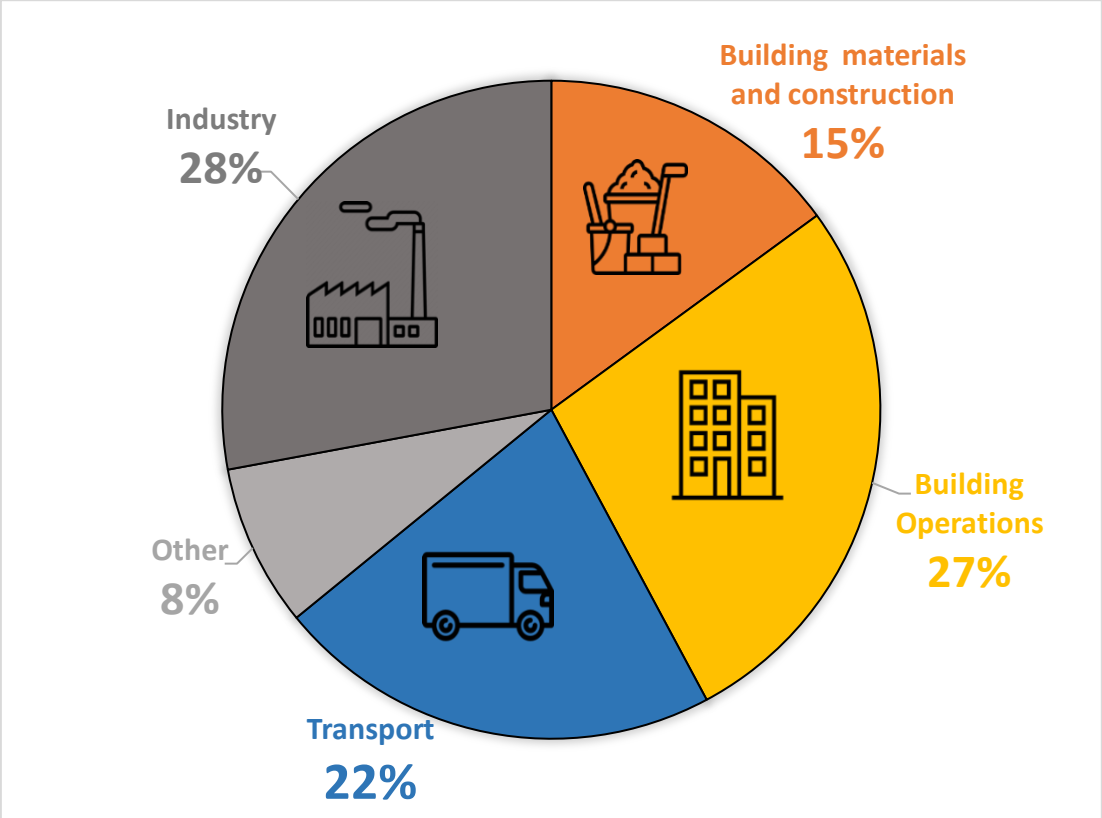


Figure 2-3: Total annual global CO_2 emissions by each sector.

A Whole Building Life Cycle Assessment (WBLCA) is a comprehensive evaluation that assesses the overall environmental performance of a building throughout its entire life cycle. This assessment follows international standards (15978 European standards for LCA on buildings), where the stages of the life cycle of buildings are separated into multiple modules, from product manufacturing through construction, use, and end-of-life processes, as shown in Figure 2-2 (European Committee for Standardization, 2011). The total life cycle of a building includes both embodied and operational carbon (IES, 2024). Operational carbon refers to the energy used to maintain indoor environments, including heating, cooling, lighting, and appliance operation, and accounts for 65% of the total carbon emitted during a building's entire lifecycle. Embodied carbon represents the total carbon dioxide emissions produced during the extraction, processing, use, and disposal of building materials, which accounts for approximately 35% of the total carbon emitted during a building's entire lifecycle (Figure 2-4).

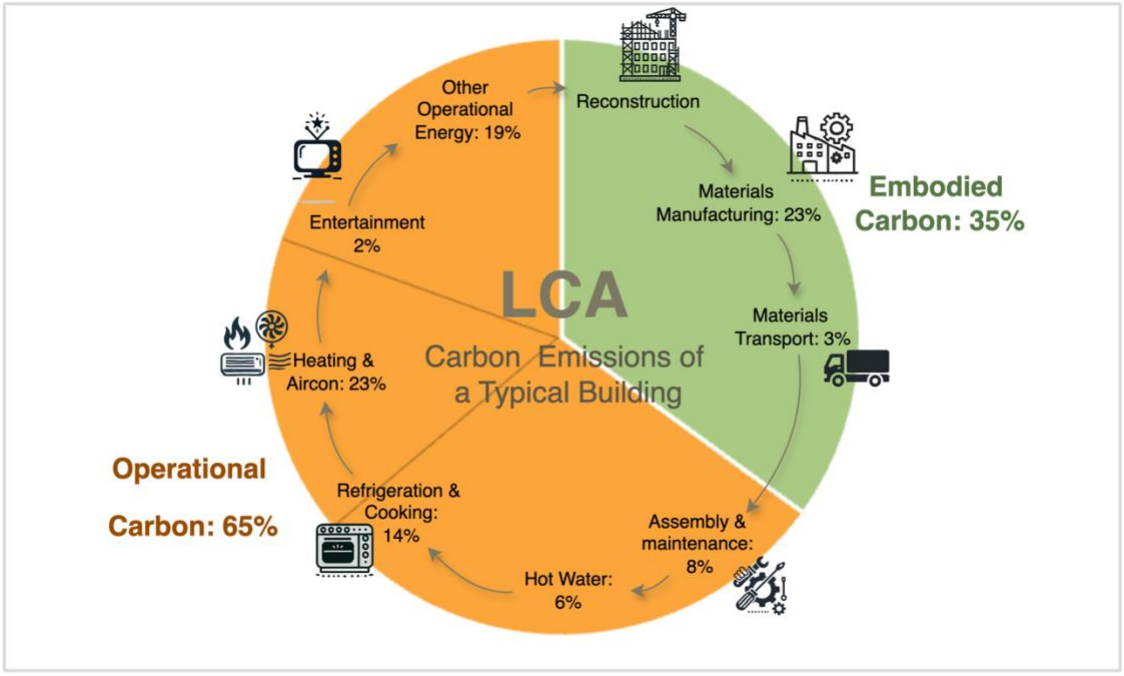


Figure 2-4: Total life cycle of a building and carbon emitted during the process of building construction.

An LCA evaluates numerous environmental effects, with carbon footprint being the one of particular interest to many builders and architects from a climate standpoint. Utilizing LCA to determine a building's embodied carbon serves two essential purposes. Firstly, it identifies areas where Engineers, architects, and decision-makers can improve to reduce the embodied energy in future constructions. Secondly, selecting construction materials with a low carbon footprint is a crucial initial step in lessening the overall environmental impact throughout a building's entire lifecycle (Hall, 2023). Some researchers are interested in investigating the environmental impacts associated with the production of different building materials, while some focus on the effects of using alternative materials in the building components and structure. Wood products are widely used in the construction sector, and research related to the environmental aspects of wood products has developed into an important research area.

2.2.1 Wood Products and LCA on their Production Level

Wood continues to evolve as a versatile and sustainable resource in the modern age. Using wood products in construction has positive environmental effects, such as lower use of fossil fuels and GHG emissions during manufacturing (Ritter et al., 2011). The demand for efficient utilization of harvested wood materials has led to a surge in research and innovation, particularly in engineered wood products (EWPs). Engineered wood is defined as any structural product made from roundwood that has been reduced into smaller pieces or a structural product made from residue materials from wood processing operations (Guss, 1995). EWPs have developed into various products over the last hundred years, each being created to perform exceptionally well in particular structural uses (Gong,

2022). Traditional EWP can be produced from wood particles coupled with synthetic resin or natural adhesives to create a variety of products, including oriented strand board (OSB), medium-density fiberboard (MDF), high-density fiberboard (HDF), particle boards, and more (Sahoo et al., 2019).

In the family of EWPs, mass timber products (MTP) have been created as the main framework for tall wood buildings or high-rise buildings. MTPs are EWPs with large section sizes that offer the construction industry viable alternatives to structural steel and reinforced concrete (Harte, 2017). These products include large-scaled, thick-panel products, such as cross-laminated timber (CLT) and structural composite lumber (SCL), as well as adhesively or mechanically laminated linear elements like glue-laminated timber (GLT), nail-laminated timber (NLT), and dowel-laminated timber (DLT) (Gong, 2019). EWPs can be categorized by the orientation of the lamination (parallel or cross-laminated) or by the wood element (fiber, strand, veneer, and lumber) used in the manufacturing of these products (Gong, 2022). Figure 2-5 offers a visual glimpse into some of the commonly used EWPs (Gong, 2022).

Figure 2-5: Major types of engineered wood products and their abbreviations (source: images obtained from archiproducts. com, canac.ca, diy.com, globalsources.com, leben.co.in, nrcan.gc.ca, and structurecraft.com).

Moreover, lumber, the focus of this thesis' cradle-to-gate LCA, is a product manufactured from logs and includes boards, dimension lumber, and timbers. In North America, most lumber is softwood dimension lumber, typically with thicknesses ranging from 38 to 89 mm, widths from 38 to 184 mm, and lengths up to 5 meters (Gong, 2019). Lumber is widely used in light-frame construction and plays a crucial role in mass timber construction, where it is used to manufacture products like CLT, Glulam, NLT, or DLT (Sahoo et al., 2019). Using these items in construction has several benefits, the most notable of which is their environmental performance. Using traditional wood products and EWP is considered an environmentally friendly choice. Due to several factors discussed in the following, governments promote this as a part of sustainable development and strategies to mitigate climate change (Natural Resources Canada, 2019).

Wood's carbon sequestration and storage characteristics make it a preferred material to other alternatives (Bergman & Bowe, 2008). Carbon sequestration is removing carbon from the atmosphere and cycling it. At the same time, storage means holding the carbon in products for a certain amount of service life, which reduces the amount of CO_2 in the atmosphere temporarily (Brandão et al., 2013). Approximately 50% of the dry weight of the wood products contains carbon. By storing carbon absorbed from the atmosphere, using wood products in construction offers an extra environmental advantage due to the longer service life than other wood products, such as paper, packages, panels, and more (Figure 2-6). The most recent study shows that the lifespan of wood-based products ranges from 2 months for newspapers to 75 years for building elements. The benefit to the ecosystem increases with the length of this period (Beyer et al., 2006). However, depending on the end of life of the treatment, biogenic carbon emissions at the end of the life of the wood

product may be released partially or entirely back into the atmosphere (Puettmann, 2022). In other words, different types of wood product disposals at the end of their life have diverse environmental impacts. Although the carbon storage in wood products is not permanent, it should be included when estimating the overall carbon pool (Sathre & O'Connor, 2010).

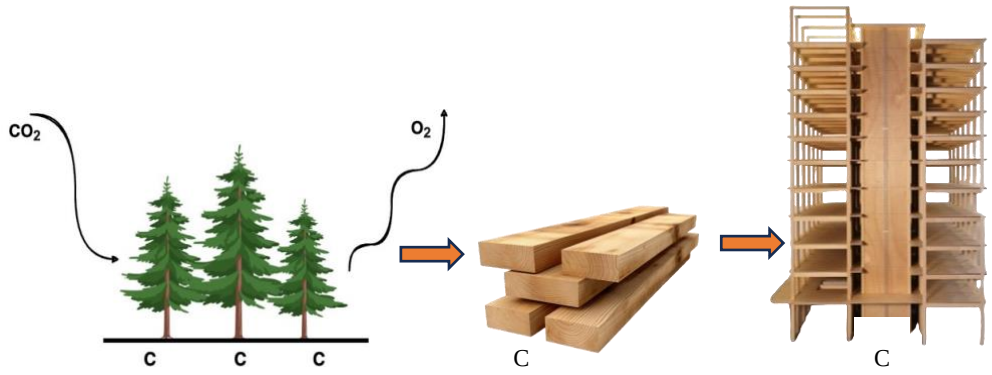


Figure 2-6: Carbon sequestrated by trees and stored in wood products during the certain service life.

Calculating the carbon stored in buildings EWPs can be accomplished using a straightforward static method as outlined in Equation (1) below (Gu et al., 2022):

$$\text{Carbon Stored (in kg)} = \text{Volume of EWP (in m}^3\text{)} \times \text{Density (in kg/m}^3\text{)} \times (1 - \text{MC}) \times [\text{Carbon Content in Wood}] \times [\text{Molar Mass of } CO_2 / \text{Molar Mass of Carbon}] \quad (1)$$

(MC) represents the moisture content percentage of the EWP.

The carbon content in wood is approximately 50% (Bergman et al. 2014a).

The molar mass of CO_2 is 44, and the molar mass of carbon is 12.

In the journal Nature Sustainability, researchers at the Potsdam Institute for Climate Impact Research in Germany explored four possible scenarios for using timber in building construction over the next 30 years (Think Wood, n.d.). The first scenario, "business as usual," would result in only 0.5% of buildings being made of wood while the rest would be made of concrete and steel. The other three scenarios included 10, 50, and 90% of new buildings constructed with wood. Their study found that the lowest scenario would result in the storage of 10 million tonnes of carbon per year, and the highest scenario would result in nearly 700 million tonnes. The researchers pointed out that buildings are an opportunity for long-term carbon storage, as most used construction materials like steel and concrete do not store carbon (Think Wood, n.d.). The Softwood Lumber Board (Softwood Lumber Board & FPInnovations, 2020) predicts that by 2035, mass timber products used in U.S. residential and non-residential construction are expected to sequester approximately 6 million metric tonnes of CO_2 over the lifespans of these buildings. This projection is based

on the anticipated growth in mass timber adoption, which will require a significant volume of softwood lumber sourced for its production. Consequently, timber buildings constructed in urban areas can be seen as transferring carbon storage from forests to cities (Gu et al., 2022).

Carbon neutrality is another important aspect of using wood products, meaning carbon emitted from wood biomass during combustion is assumed to be biogenic in contrast to fossil carbon. Biogenic carbon emissions, as defined by the EPA, are associated with the natural carbon cycle. Unlike fossil carbon emissions, which come from coal, natural gas, and petroleum combustion, the release of CO_2 from burning biomass is categorized as biogenic carbon. This carbon is offset by the carbon absorbed by newly planted trees. Biogenic carbon related to wood products may originate from various sources, including post-harvest residues, biological-based fuels, and carbon release after landfilling products. Biogenic carbon is the primary emission from the processing of wood products since it primarily relies on biomass energy from sources like post-harvest leftovers and mill byproducts (Puettmann & Wilson, 2007). Therefore, it is essential to account for biogenic carbon when assessing the net carbon balance of wood products (Meil et al., 2009). Bergman and colleagues (2014a) explained that a distinction between biogenic and fossil energy sources is frequently made in life-cycle-based analyses because biomass releases carbon that is a part of the biogenic carbon cycle as opposed to the carbon that has been locked up in the earth for millions of years when fossil fuels are burned. In other words, according to the International Energy Agency (International Energy Agency, n.d.), while using fossil fuels raises the overall carbon content of the biosphere-atmosphere system, bioenergy systems still operate within this system (Figure 2-7).

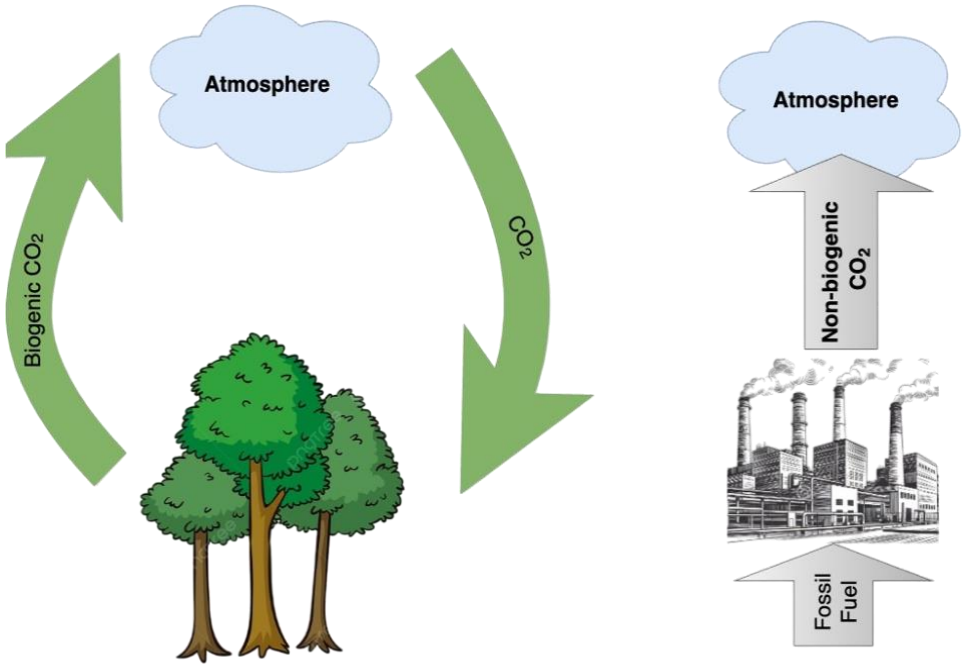


Figure 2-7: Fossil vs biogenic CO_2 emissions during burning (IEA, n.d.).

Table 2-3 presents a study's cradle-to-gate GWP analysis on a CO_2 eq mass basis, reporting emissions from burning fossil fuels and biomass throughout the manufacturing of softwood lumber at 15 sample SPF (Spruce, Pine, Fir) sawmills, which represents approximately 8% of all softwood lumber production in Canada. Additionally, it provides softwood lumber's net cradle-to-gate carbon balance. On a CO_2 eq mass basis, producing 1 m^3 of softwood lumber produces 188 kg of GHGs, of which 52% come from burning renewable biomass, such as hog fuel. However, the same amount of softwood lumber achieves net carbon sequestration of 577 kg CO_2 eq basis thanks to its 765 kg CO_2 eq basis carbon content. According to this figure, a m^3 of softwood lumber contains nearly four times as much carbon as is released into the atmosphere during production (Meil et al. 2009).

GWP due to	**Per m^3**
Fossil fuel use	90.45
Biomass Combustion	97.19
Total	187.64
Carbon sequestered in Softwood lumber	764.55
Net Carbon Balance	
Excluding Biomass GHGs	674.10
Including Biomass GHGs	576.91

Table 2-4: GWP and net carbon balance (CO_2 eq)- softwood lumber (Meil et al. 2009).

The production of wood products involves various phases that generate emissions, which can be offset through biofuel substitution and carbon storage within the wood products. However, the benefit of wood as a renewable material tends to be ignored without life cycle analysis (Ritter et al., 2011). Careful evaluations are crucial for making well-informed choices about responsibly and sustainably using valuable forest resources (Sahoo et al., 2019).

In the United States, the impacts of the production processes for wood-based materials such plywood, softwood lumber, engineered wood products such as laminated veneer lumber (LVL), and I-joists are well documented. LCA has been performed on various wood material production processes throughout the country. For instance, the Consortium for Research on Renewable Industrial Materials (CORRIM) has developed and updated inventory data and conducted LCA analyses on softwood lumber and I-joist production in the northwestern U.S. (Puettmann et al., 2013; Puettmann et al., 2010 a). Moreover, In Canada, the Athena Institute, in collaboration with the Canadian Wood Council, has developed six industry-average LCA studies for wood products, including lumber, plywood, oriented strand board, laminated veneer lumber, glulam, and wood I-joists. These EPDs adhere to the ISO 21930:2017 standard, recognized for construction product LCAs (Athena Sustainable Materials Institute, n.d.). The amount of energy used to produce different wood products varies considerably based on the specific type of product (Petersen & Solberg, 2003; Lippke et al., 2010; Puettmann et al., 2010 b). These differences emphasize the importance of understanding the environmental impact of various wood product classifications. The report "Status of Energy Use in the Canadian Wood Products Sector" highlighted Canada's wood industry, covering both commodity and value-added

products (Meil et al., 2009). It focused on five wood-based products: softwood lumber, plywood, OSB, particleboard (PB), and MDF (Figure 2-8). The research conducted a cradle-to-gate life cycle analysis to help the industry comprehend resource usage and investigate potential solutions for reducing energy in the future.

Softwood Lumber		OSB	
Plywood		Particleboard	
MDF			

Figure 2-8: Various types of wood-based panel and lumber products.

The data presented in Figure 2-9 highlights a significant trend: as the raw material size decreases during wood product manufacturing, the energy use in the process increases. Softwood lumber and plywood retain much of the wood's original characteristics, while OSB, PB, and MDF go through more complex processes, resulting in denser products and higher energy consumption. Additionally, all products rely on electricity, diesel fuel, natural gas, and biomass, which are significant factors to consider for energy preservation. Diesel fuel consumption is primarily linked to logging and transporting activities, which may be outside the immediate influence of wood processing plants. Notably, OSB and reconstituted board products use more biomass fuels during manufacturing than plywood or softwood lumber (Meil et al., 2009).

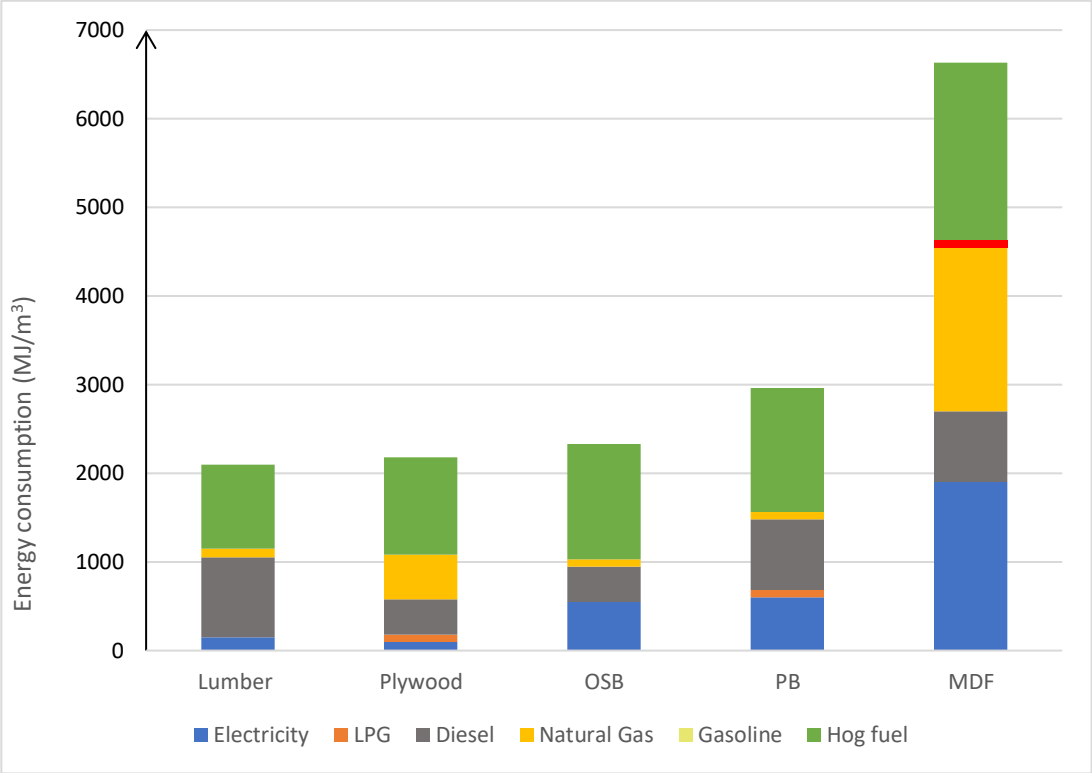
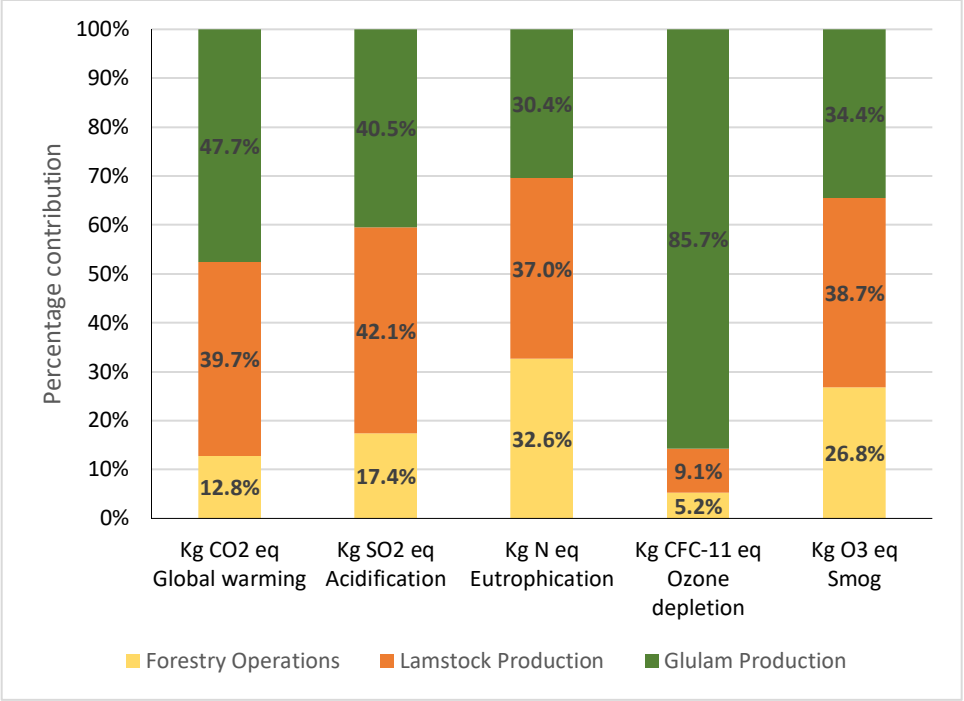


Figure 2-9: Gross cradle-to-gate primary energy use by fuel type (MJ/m^3 of product) (Meil et al., 2009).

When it comes to examples about LCA on actual MTPs, Bowers et al. (2017) conducted a cradle-to-gate LCA on glulam timber in the Pacific Northwest and Southeast U.S. The study found reduced energy use in both regions due to improved manufacturing, though transportation increased diesel and LPG consumption in the Pacific Northwest. Glulam beams were found to store more CO_2 than they emit, thanks to carbon sequestration in wood. Environmental impacts in the Pacific Northwest showed reductions in global warming and eutrophication but increased smog potential, while all impacts decreased in the Southeast. Figure 2-10 shows the contribution analysis LCIA per 1 m^3 of glulam timber production in the Pacific Northwest and Southeast. Comparing the three stages of forestry operation, lamstock (lumber prepared for glulam production), and glulam production, although in both region glulam production had the majority of contribution in GWP, in southeast is lightly higher than the pacific northwest. This is while, in contrast the lamstock production is lower in the southeast. The most significant difference was seen in the eutrophication and Ozone depletion impact categories in the two different regions.



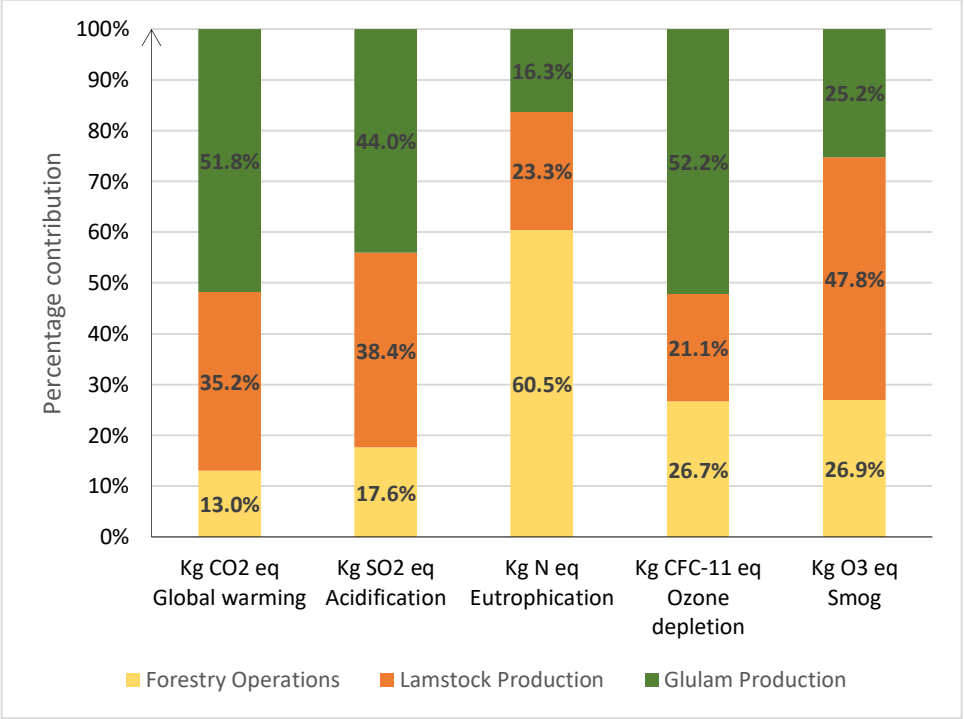


Figure 2-10: life-cycle impact assessment and contributions per life-cycle stage per m^3 of glulam production in the Pacific Northwest (top) and Southeast (bottom).

The cradle-to-gate LCA for Canadian CLT was conducted by the Athena Institute, aiming to create EPD. Based on 2011 production data, the study followed FP Innovations' guidelines and ISO 21930 principles to assess environmental impacts. The TRACI method in SimaPro found that CLT production accounts for nearly 50% of global warming effects and 53% of fossil fuel consumption in its life cycle. Notably, logging significantly increased smog impacts due to reliance on diesel-powered equipment, while lumber drying, primarily fueled by biomass, disproportionately affected fossil fuel use. CLT manufacturing was the only factor contributing to ozone depletion in the life cycle. Figure 2-11 demonstrates the contribution of each stage for different impact categories.

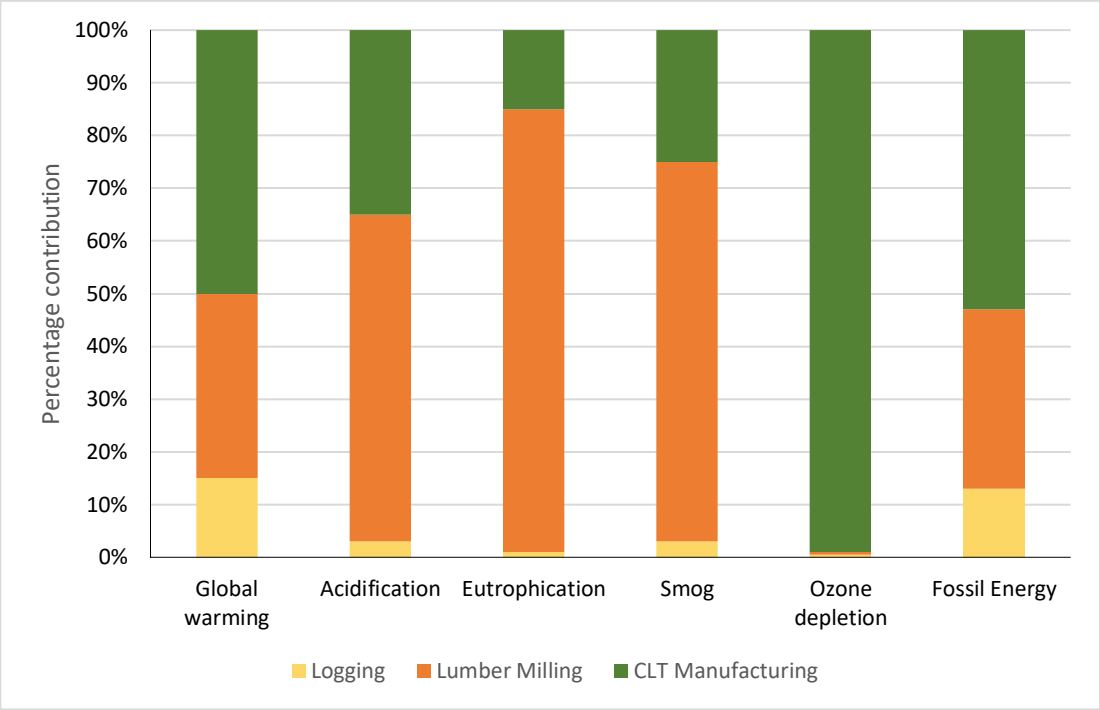


Figure 2-11: Cradle-to-gate CLT LCIA results.

The gate-to-gate CLT LCIA results demonstrated that transporting lumber and resin production significantly impacted manufacturing stage outcomes. Transportation of lumber, which ranged from 125 to 530 km to the facilities, was responsible for 28% of the fossil fuel use and 37% of the global warming impact. In addition to significantly impacting ozone depletion, resin consumption was responsible for 49% of fossil energy use and 43% of GWP (Figure 2-12) (Athena Sustainable Materials Institute, 2013).

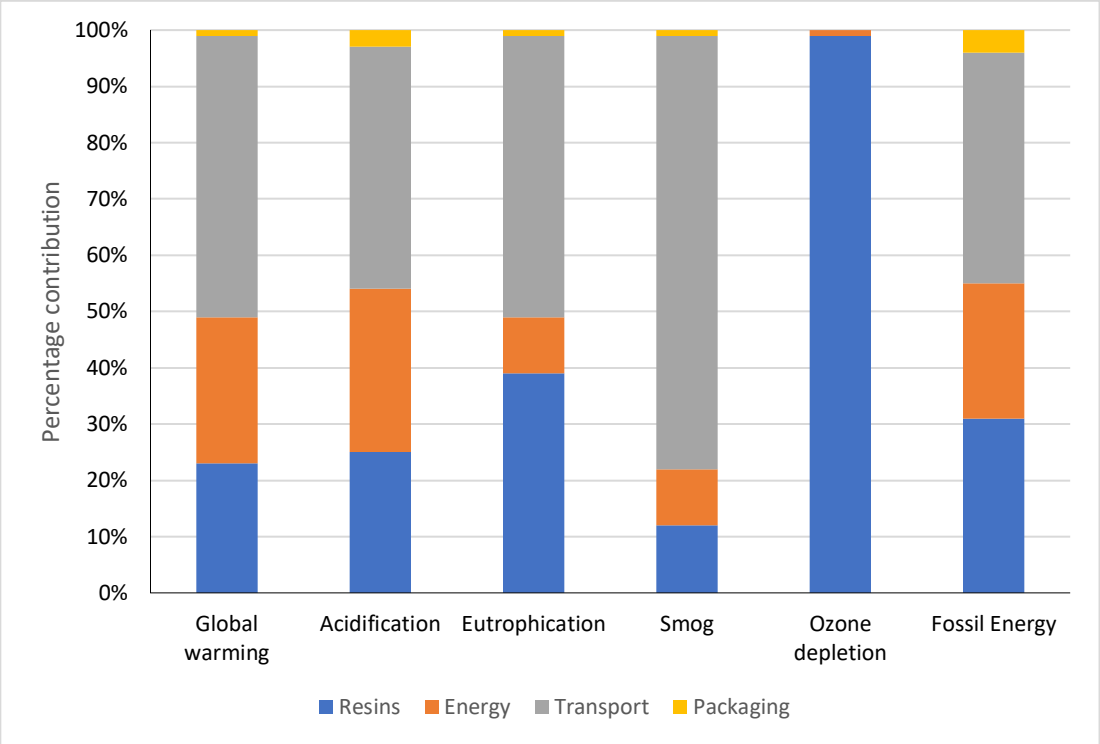
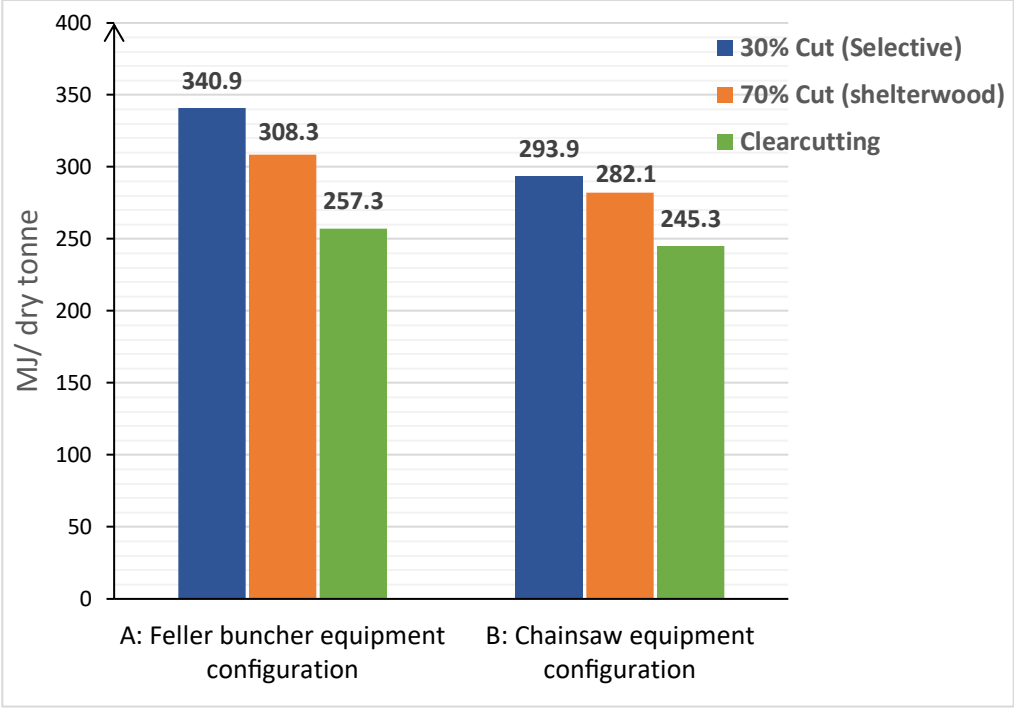


Figure 2-12: Gate-to-gate CLT LCIA results.

The first stage of LCA, resource extraction, is known as harvesting in wood products LCA, and it is the same for all types of wood products. The harvesting of trees uses a lot of fossil fuels since it entirely depends on diesel for large machines and gasoline for chainsawing and crew transportation (Mahalle, 2010). Abbas & Handler (2018) conducted, using the Ecoinvent database and the SimaPro LCA model, an LCA study on hardwood and softwood harvest and transport operations in Tennessee, USA. Tennessee's forests are primarily composed of hardwood species, with oak-hickory accounting for 71%, followed by 12% oak-pine, 10% loblolly-shortleaf pine, 5% oak-gum-cypress, and 2% classified as other types (TN Division of Forestry, 2009). They revealed that chainsaw-based harvesting had lower GHG emissions and fossil energy demand than feller buncher-based methods. Moreover, they emphasized that alterations in harvesting intensity, such as transitioning from selective to clearcutting, yielded reduced emissions per tonne of harvested wood (Figure 2-13). Notably, truck transportation of roundwood emerged as an environmental factor, with transport distances playing a crucial role. Three transport distance scenarios were considered to generate results for various round-trip distances: 50 km, a baseline distance of 150 km, and 250 km. Additionally, this study compared wood harvesting and transport systems in Sweden and Canada with findings from Fuente et al. (2017). In Sweden, GHG emissions were notably lower compared to the values observed in Tennessee. This difference is likely attributed to Sweden's more extended harvesting periods and more optimized plantation settings. Conversely, Canadian harvesting emissions were higher than those of Sweden. Despite significantly lower harvesting emissions than the practice in Tennessee (approximately 50% lower), transport emissions

were comparable across these studies. This comparison underscores the significant impact of harvesting methods, transport distances, and regional practices on GHG emissions within wood supply chains. It also highlights the potential benefits of different approaches, such as Sweden's intensive and mechanized methods, in mitigating overall emissions despite facing similar challenges in transportation emissions (Abbas & Handler, 2018). Figure 2-14 illustrates the GHG emissions associated with different transportation distances and the variation in harvesting methods.



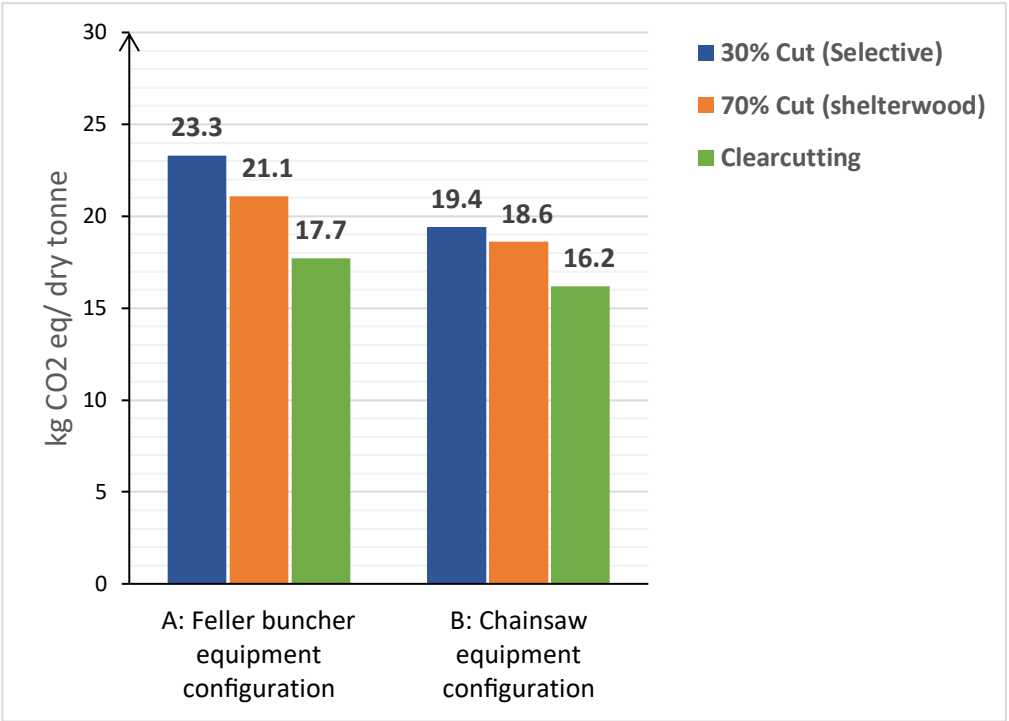


Figure 2-13: Energy consumption (top) and CO_2 emissions (bottom) by logging methods and harvesting intensities.

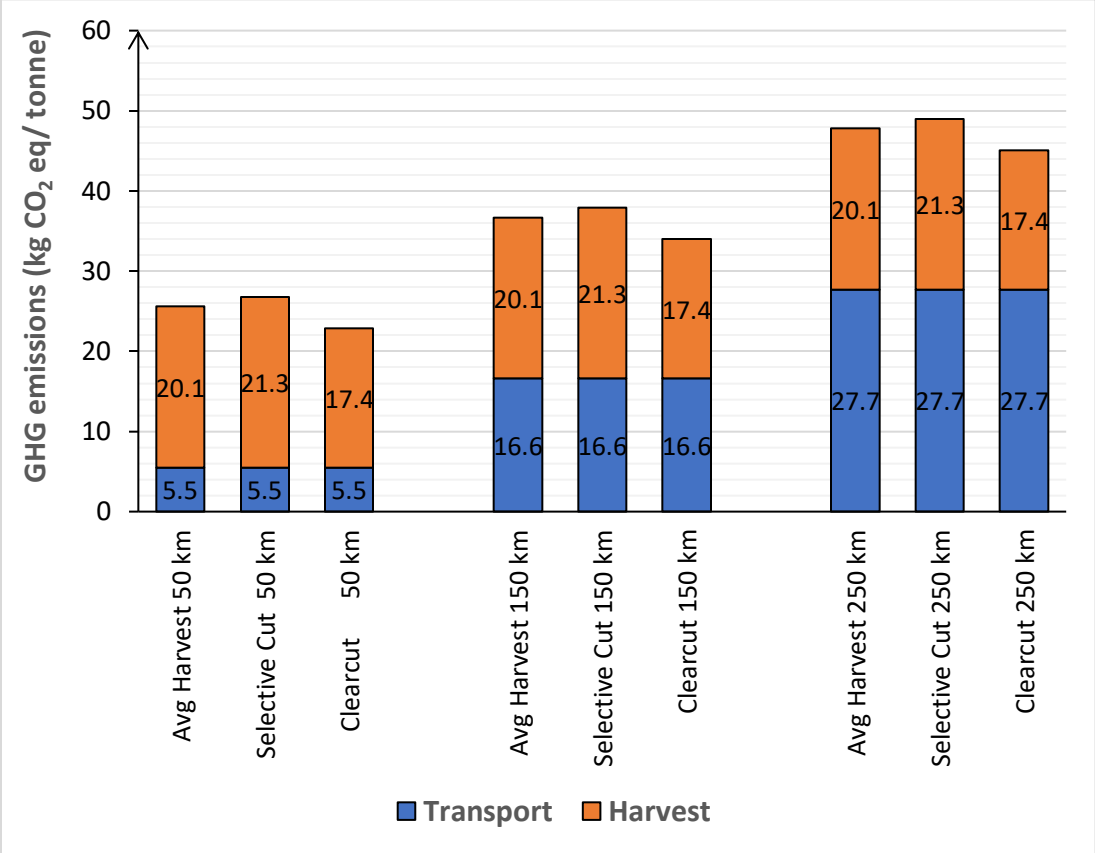


Figure 2-14: GHG emissions associated with different transportation distances and the variation in harvesting intensity.

Studies have shown that manufacturing contributes the most to CO_2 emissions and energy consumption in product life stages. According to Miner (2010), manufacturing accounts for 55% of total emissions across the value chain, equating to around 490 million tonnes of CO_2 equivalent annually. The leading cause of these emissions is the burning of fuel in manufacturing plants, which significantly impacts the sector's GWP (Adhikari & Ozarska, 2018). The Canadian wood products industry has been analyzed in the report "Status of energy use in Canadian wood products sector" conducted by FPInnovations (Meil et al., 2009), which reveals that kiln drying is the most energy-intensive process, consuming 66% of the total energy required to produce the softwood lumber. Other energy-consuming unit processes include sawing, surface planning, and packaging. Sawing alone consumes 70% of the electricity purchased, while 73% of natural gas and 97% of biomass thermal fuels are used in kiln drying (Figure 2-15) (Meil et al., 2009). Also, several studies have concluded that the sawing process consumes the highest percentage of electrical energy (Bergman & Bowe, 2008; Milota & Puettmann, 2017; Bergman et al., 2014 b; Sahoo et al., 2021).

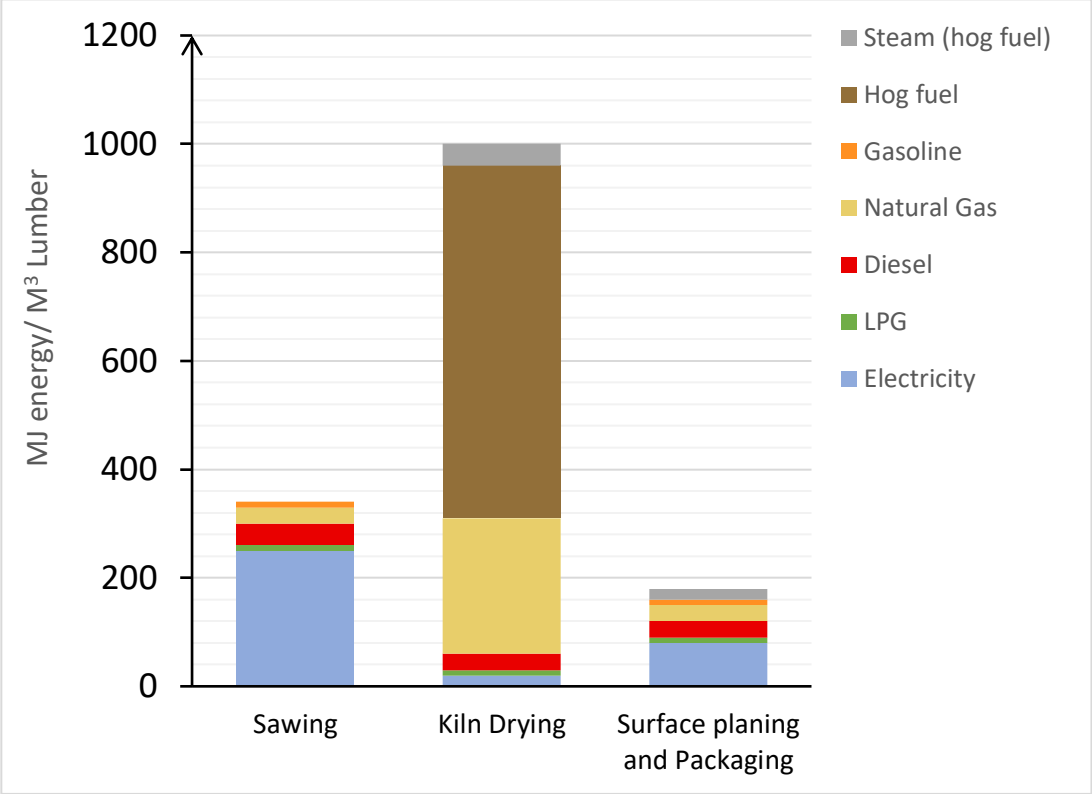


Figure 2-15: Energy sources used in various unit processes of lumber production, including sawing, kiln drying, and surface planing/packaging.

Comstock (1975) said that the energy needed for drying hardwood lumber is around 70–80% of the "total" energy required to produce it. This aligns with findings that the drying process is a significant energy consumer in lumber production (Bergman & Bowe, 2008; Milota et al., 2005; Bergmann & Bowe, 2010; Puettmann et al., 2010 b). Most of the thermal energy and electricity needed at the mill is produced by burning a fuel, such as wood or natural gas, or leftover green wood waste. Thermal energy is typically produced on-site from biomass or wood residues (Puettmann et al., 2010 b; Sahoo et al., 2021), primarily for drying timber. According to Milota & Puettmann (2017), 91% of wood residue used for boiler inputs in softwood lumber production is locally sourced, with 9% imported. However, electricity from off-site sources like coal and natural gas is mainly used for sawing, though some mills utilize co-generation from wood residues for electricity generation.

As discussed before, fossil fuel emissions are non-renewable and have a significant effect on the rise in atmospheric GHG concentration and environmental impact (Prentice et al., 2001; Hussain et al., 2014), while renewable energy sources, such as wood biomass are those that are environmentally friendly. These pose fewer risks to public health and the environment (Adhikari & Ozarska, 2018; Bergman & Bowe, 2008). As a result, there is a greater need to generate energy from facility wood waste to reduce GHG emissions, notably from fossil fuels like coal (Kelley et al., 2020). Dionco-Adetayo (2001) discovered that out of 1 m^3 of a tree cut and taken from the forest, around 50% goes to waste in the form of damaged residuals, followed by abandoned logs (3.75%), stumps (10%), tops and branches (33.75%), and butt trimmings (2.5%). However, Sathre & Gustavsson (2011) demonstrated that logging waste could be collected and utilized as fuel to produce energy.

Puettmann & Lippke (2012) conducted a study using the SimaPro LCA software tool (Pre Consultants, 2012), comparing the impact on net carbon emissions by substituting wood pellets, mill waste, and forest waste for natural gas in electricity generation or heat production for drying. Their results showed that using woody biomass for heat energy could significantly reduce carbon emissions compared to fossil fuels. Their study also found that substituting 100% natural gas boiler inputs with 46% wood waste and 54% gas (baseline scenario) will result in a 58% increase in GHG emission or GWP. However, using wood pellets and mill wastes together will reduce the GWP by 33% over the baseline scenario, and the most significant decrease of 47% came from using forest residuals instead of natural gas. Emissions from mill waste that were utilized to produce energy were treated as carbon neutral and substituted the fossil fuels (Sharma & Wang, 2011) (figure 2-16).

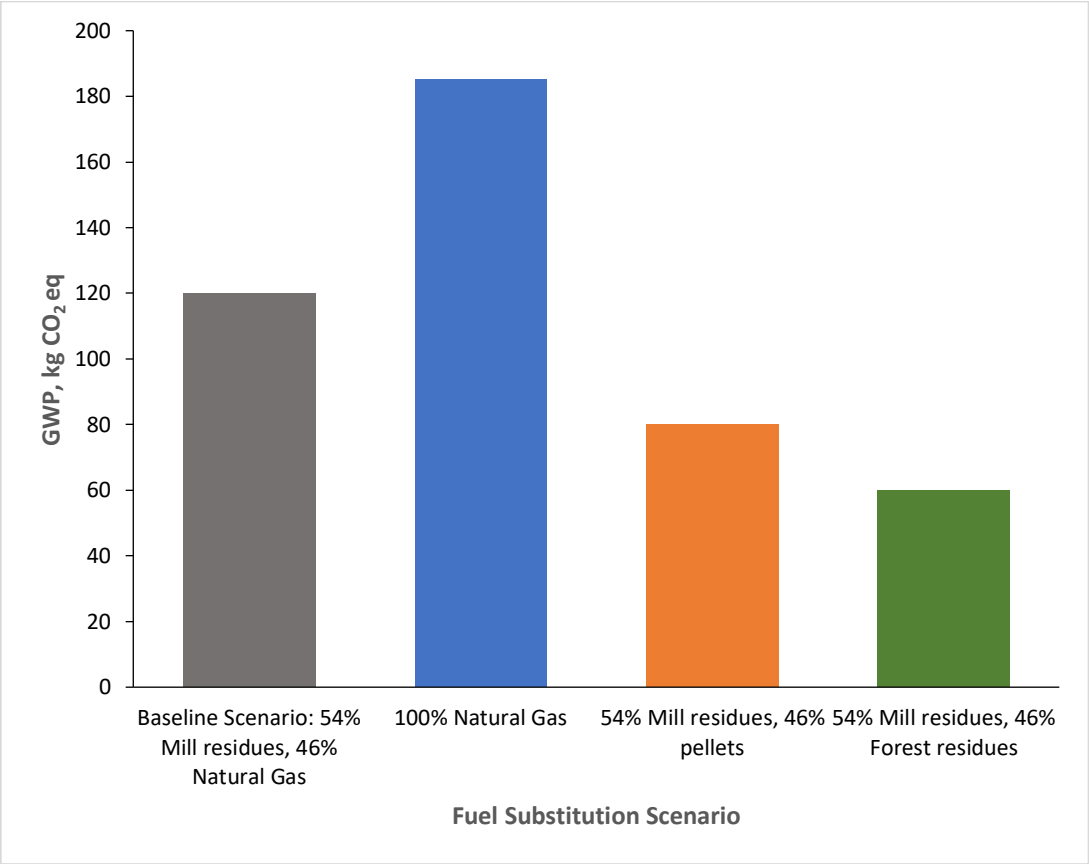


Figure 2-16: GWP emissions from fossil fuels only, expressed in kg of CO_2 eq when producing 1 m^3 Inland Northwest kiln-dried lumber under different boiler fuel scenarios.

In 2014, Bergman et al. conducted a gate-to-gate LCA of dry redwood lumber using survey data from local sawmills collected in 2010. Table 2-4 compares their previous work in 2014 with their recent study using 2017 data. The results showed a 30% increase in total primary energy used to produce redwood lumber (Bergman et al., 2014b). However, the total cradle-to-gate GHG emissions were reduced due to using renewable energy sources and heat from woody biomass.

Table 2-5: LCIA comparison between previous data, based on 2010 industry surveys and recent study data, based on 2017 industry surveys on redwood lumber production in northern California, USA (Bergman et al., 2014a).

Impact category	Unit	study based on 2017 industry data	study based on 2010 industry data	Change
GWP (Fossil)	kg CO_2 eq	22.81	57.4	-60
Ozone depletion	kg CFC11 eq	8.07E-07	3.69E-06	-78
Eutrophication	kg N eq	5.79E-02	2.34E-02	148
Smog	kg O_3 eq	4.46	6.61	-33
Non-renewable fossil and nuclear	MJ	357.78	1,023	-65
Renewable (solar, wind, hydro)	MJ	1,354.49	317	327

Moreover, the sources of energy can be different in the different regions of product manufacturing, which can also play a significant role in the environmental impacts due to the variation in technology and fuel used to produce electricity or other energy sources in different areas. Hydro generates most electricity in the Pacific Northwest (PNW) USA. In contrast, in the Southeast (SE) USA, coal is the primary source of energy for lumber production (Milota & Puettmann, 2017). This discrepancy resulted in a lower GWP in the PNW region than in the SE region (Figure 2-17).

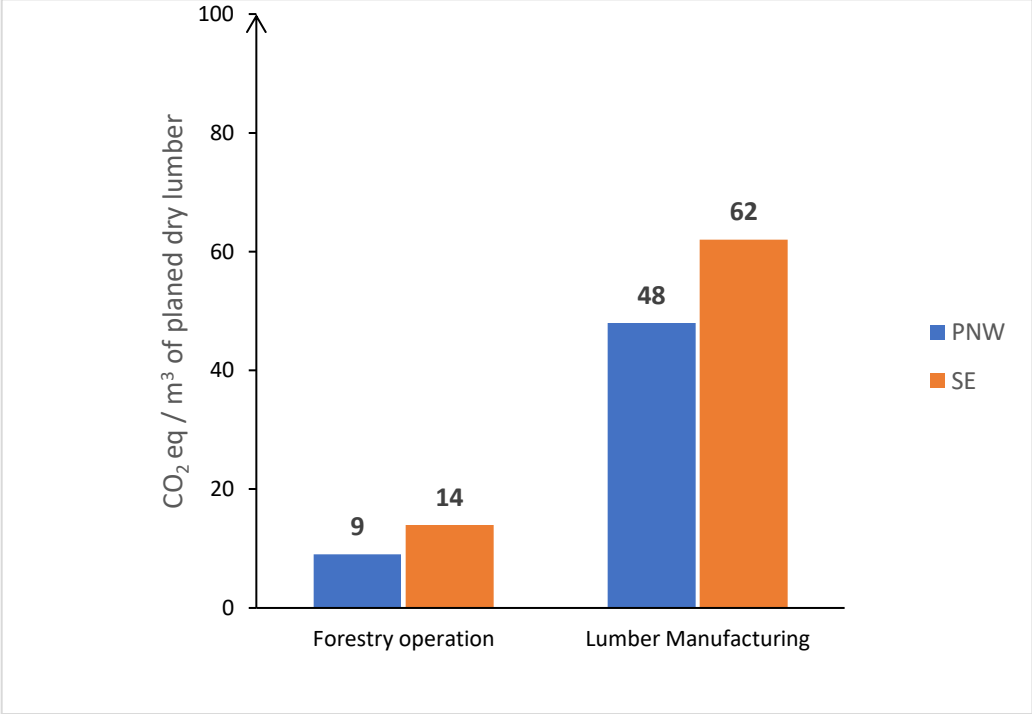


Figure 2-17: Comparison of CO_2 eq emissions in forestry operations and lumber manufacturing between the Pacific Northwest (PNW) and Southeast (SE) regions.

The energy consumption among different wood species with varying densities during the manufacturing process also affects the result of the LCA study. Bergman & Bowe (2008) and Puettmann et al. (2010a) reported that softwood lumber required less electrical and thermal energy in production when compared to hardwood timber, as hardwood lumber required more thermal energy for drying due to its higher density and lower final moisture content (MC) than softwood lumber. Also, the sawing process for hardwoods would use more electrical energy due to their higher density and smaller dimensions than softwoods (Figure 2-18) (Bergman & Bowe, 2008).

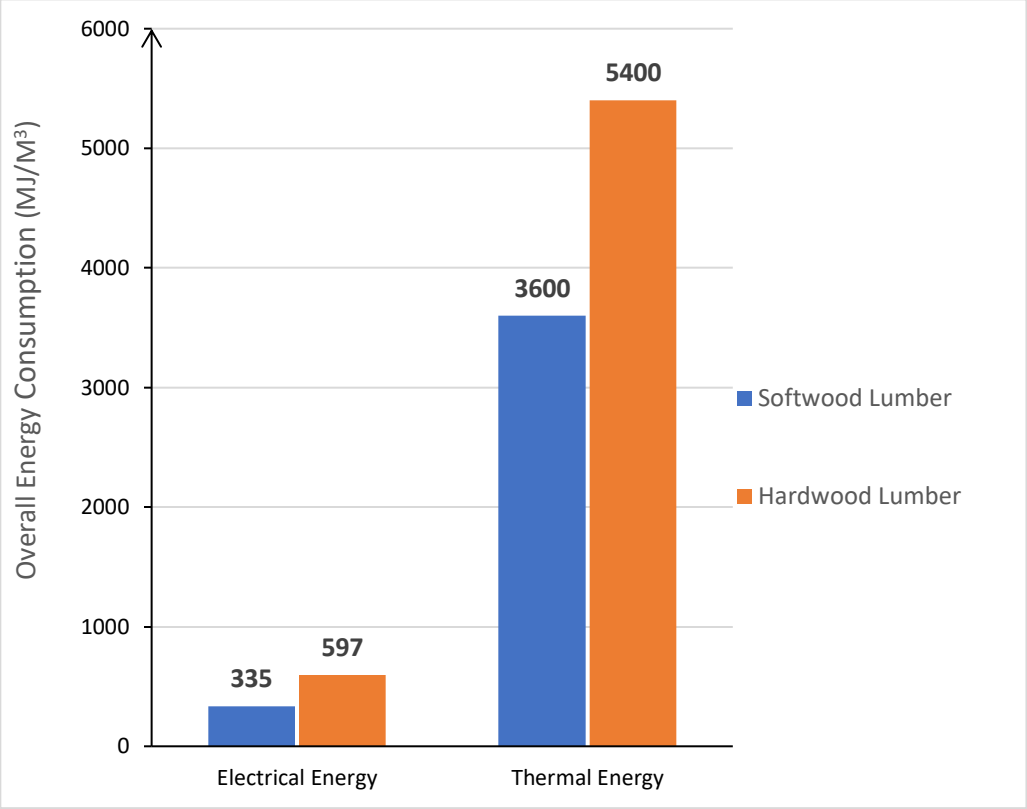
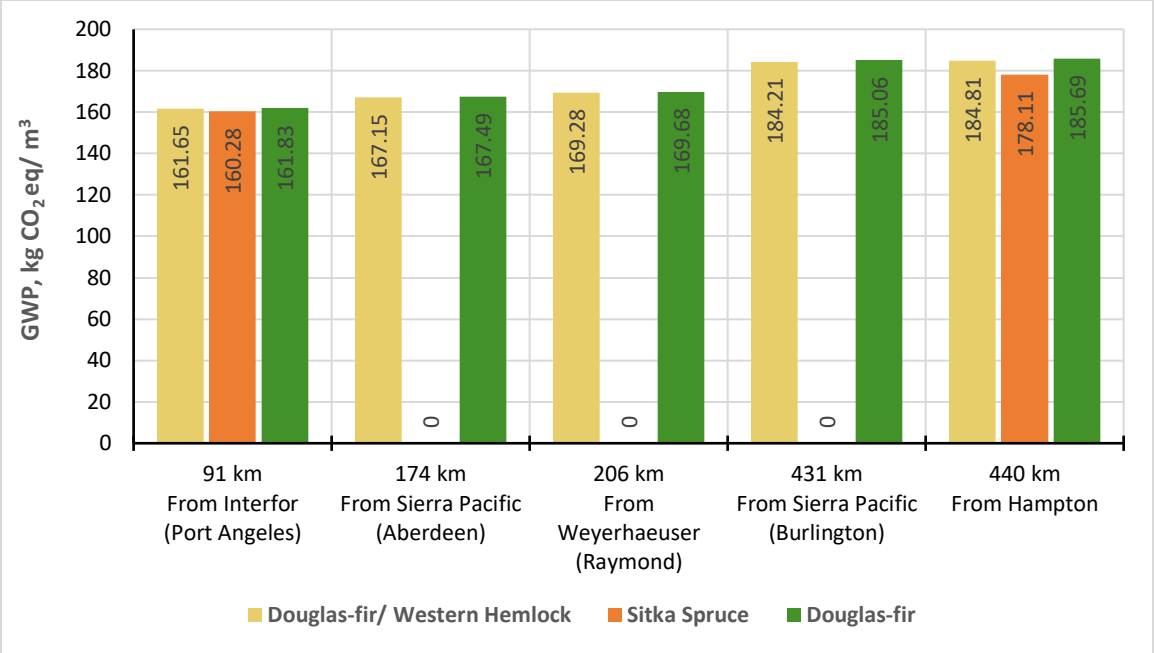


Figure 2-18: Comparison of hardwood to softwood lumber energy use.

Chen et al. (2019) conducted a comprehensive LCA on CLT produced in the Western Washington region of the United States. They aimed to analyze the environmental impacts related to transportation, location, and the mix of wood species in CLT panels. The study considered the entire lifecycle, from seedling to transportation and construction on-site. To simplify the analysis, the researchers made certain assumptions, including uniform density and MC of the wood used in production. They assumed that 1.21 m^3 of lumber was needed to produce 1 m^3 of CLT panel, and the construction site was located in Seattle, WA, USA. Five impact categories, including GWP, AP, EP, and ODP, were used for the environmental evaluation. The results indicated that sourcing local lumber and using lighter wood species in CLT manufacturing facilities could lead to a 14% reduction in the overall GWP of the CLT panels. The study revealed that the worst-case scenario for GWP was observed when using Douglas-fir lumber at a CLT mill located in Forks, resulting in 185.69 kg of CO_2 eq/m^3 of CLT panels. However, using Sitka spruce as the lumber species could lower this value to 160.28 kg CO_2 eq/m^3. Further sourcing of CLT from a mill in Darrington while still using Stika spruce could reduce the GWP even more to 156.7 kg CO_2 eq/m^3 (Figure 2-19). The study also suggested that choosing lighter lumber from slightly distant suppliers could yield similar environmental benefits as sourcing high-density lumber locally.



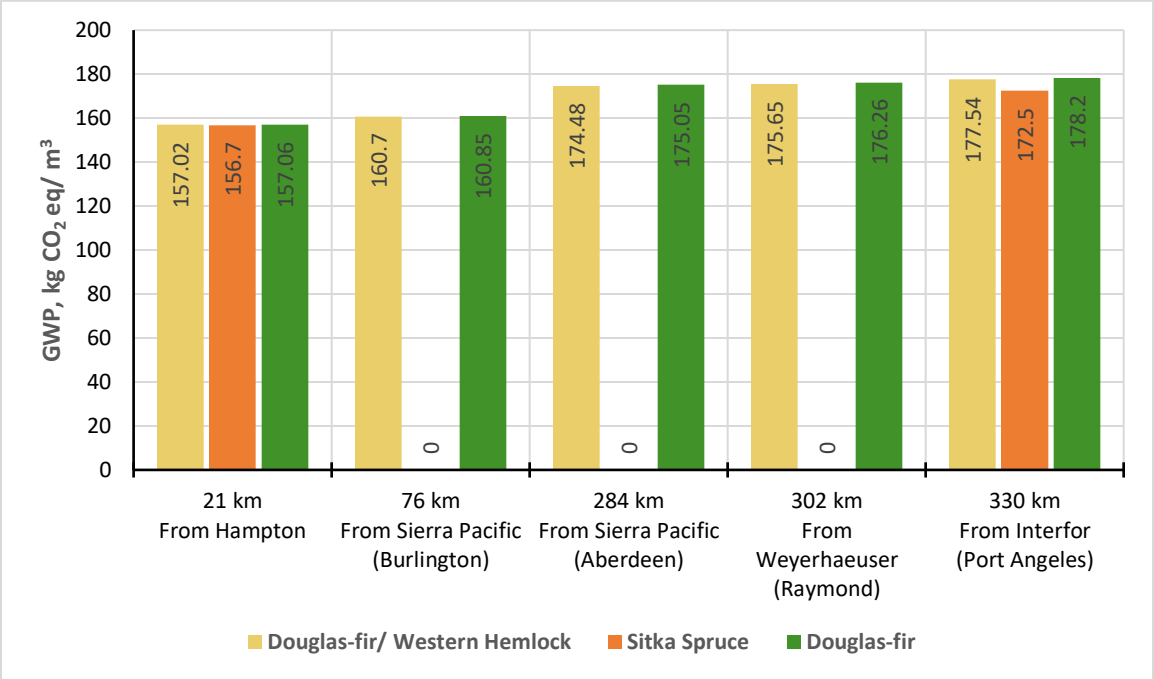


Figure 2-19: Comparison of total GWP of CLT production under different case scenarios based on wood species and transportation distances, excluding transportation of CLT to construction site (unit: 1 m^3 of CLT) (Chen et al., 2019).

In summary, LCA has been used in the wood industry to evaluate the environmental performance of lumber and other wood products such as CLT, revealing that many factors can influence the results. Key factors include the type of fuel used during manufacturing, which significantly affects energy consumption and emissions. Additionally, accounting for biogenic carbon highlights that the net carbon stored in wood consistently exceeds the emissions generated during production. This underscores the carbon storage benefits of wood products and their role in reducing overall environmental impacts.

2.2.2 LCA on Building Structure

To effectively compare the environmental performance of traditional building materials with mass timber materials, it is necessary to conduct an LCA analysis on two buildings with similar functions, purpose, and life span. For example, comparing a residential building constructed from steel with one using mass timber, both designed for a 60-year life span, allows for a direct comparison of their environmental impacts. Numerous studies, such as those by Jensen (2020), Simonen (2019), and Gu & Bergman (2018), have utilized LCAs to quantify the reduction in embodied carbon associated with the use of mass timber.

LCA offers comprehensive tracking and counting of inputs and outputs for all assemblies and subassemblies—every panel, fastener, finish material, coating, and other structural component. This level of detail is vital when assessing a complex "product" like a building (Hall, 2023). For instance, tracking all the inputs and outputs for all the assemblies of floor 6m x 6m structure in an office building with two different solutions (Steel deck and Wood solution) makes it possible to analyze and compare the GHG emissions and their impact on the environment (Figure 2-20). Properly defining all components and assigning their

related materials within the database enables a thorough analysis of the environmental impacts associated with each construction design.

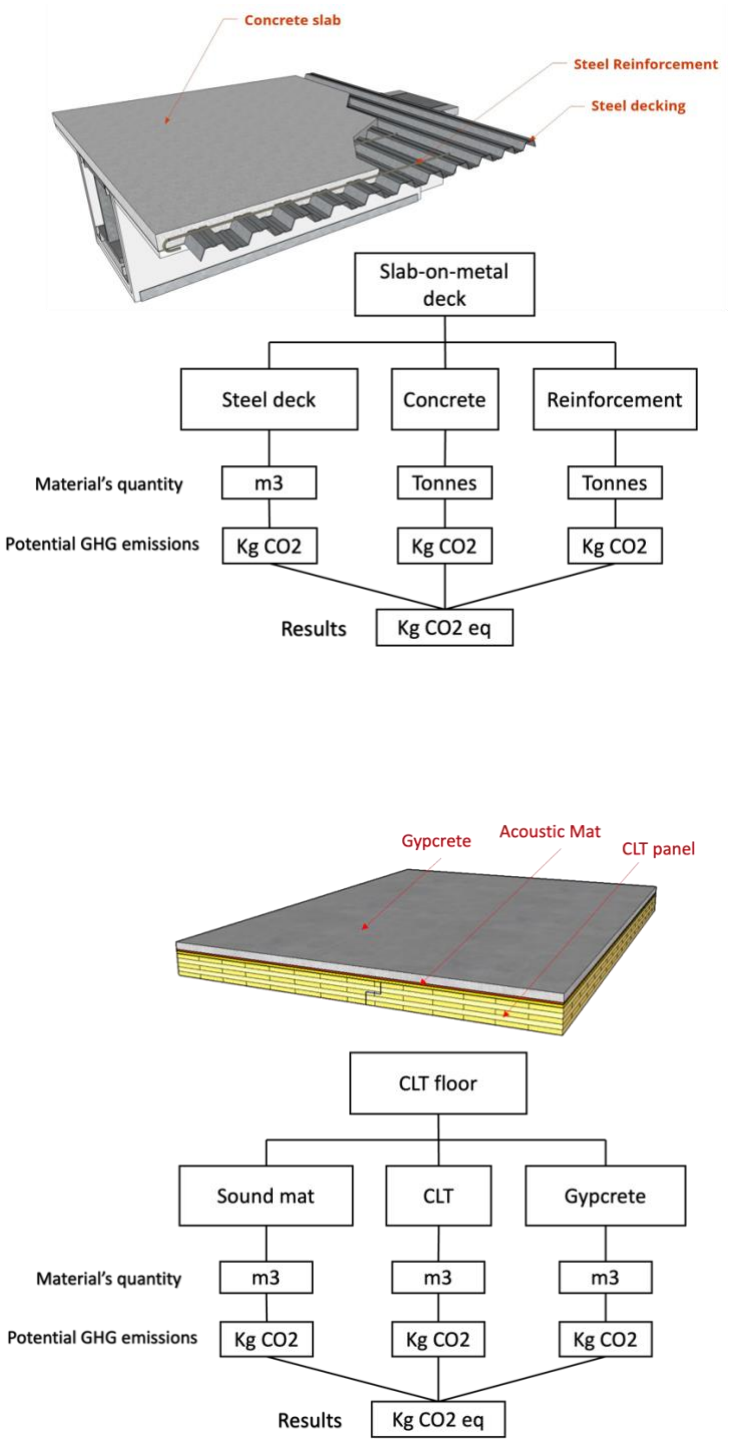


Figure 2-20: Example of input and output calculations for a 6m x 6m office building floor structure, comparing two solutions—steel deck and CLT floor assembly.

Teshnizi et al. (2018) conducted a cradle-to-grave LCA study comparing two high-rise student residential buildings at the University of British Columbia, Vancouver, Canada: one built with a hybrid mass-timber design and the other using traditional reinforced concrete. The analysis, covering a 100-year lifespan, focused on key elements such as the structure, envelope, interior partitions, and finishes, utilizing the Athena LCA tool. Detailed data was gathered through Revit models and quantity takeoff software to assess the environmental impacts of both buildings. The results demonstrated that the mass timber building had a lower environmental impact in 5 out of 6 categories, with notable reductions such as 25% lower GWP and 18% less fossil fuel depletion compared to the concrete building (Figure 2-21). The minor benefit observed was a 9% reduction in smog potential, while the mass timber design showed a 13% higher impact in the ozone depletion category.

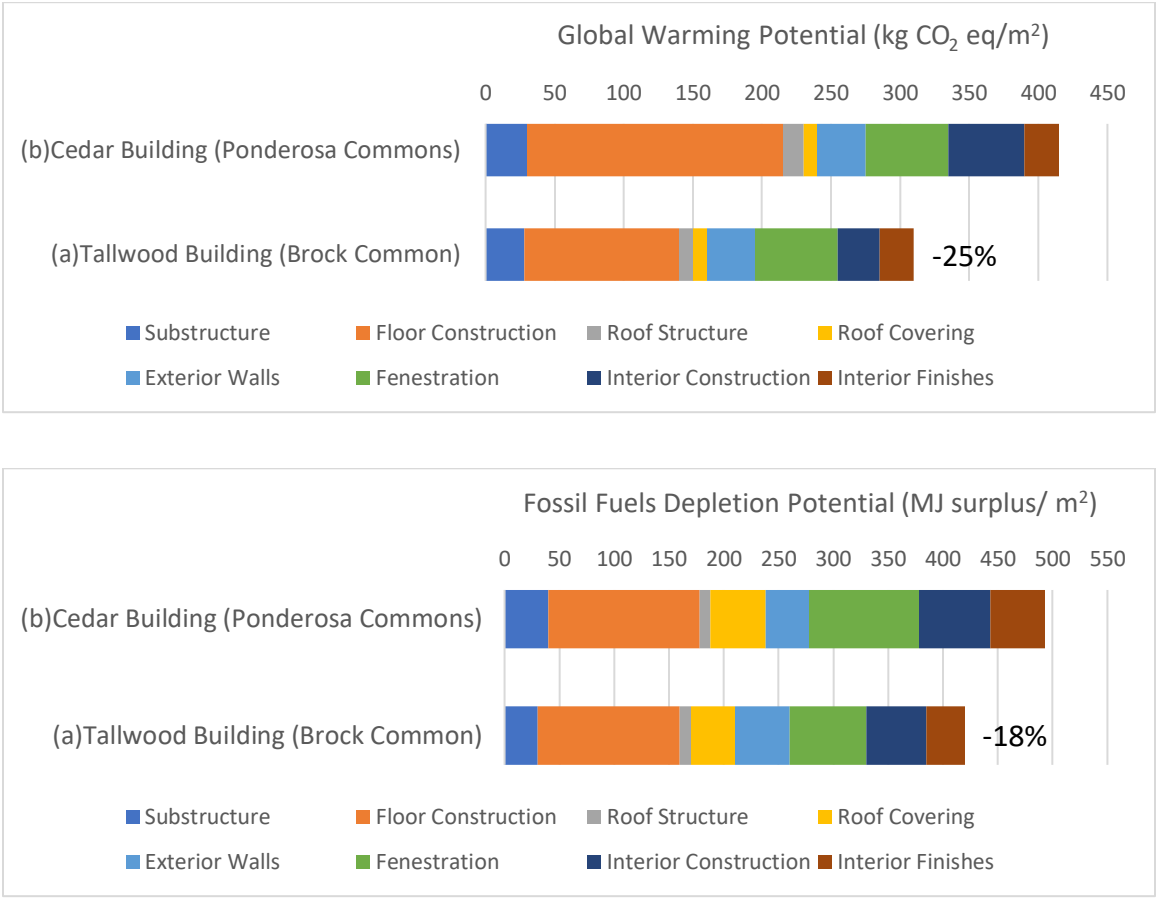


Figure 2-21: Comparison of GWP per m² between a mass timber building (Tallwood Building, Brock Commons) and a concrete building (Cedar Building, Ponderosa Commons) (top). Comparison of fossil fuel depletion potential per m² for the same mass timber and concrete buildings (bottom) (Teshnizi et al., 2018).

Chen et al. (2020) conducted a cradle-to-site LCA comparing a 12-story mass timber building in Portland, Oregon, with an alternative concrete building material. Using SimaPro and Athena Impact Estimator software, the study found that the mass timber building's GWP was 18% lower than the concrete building. The mass timber structure also outperformed in eutrophication, while the concrete building had better result in smog and acidification impacts. Ozone depletion was nearly identical in both buildings. This study offers valuable insights for the construction industry and policymakers aiming for more sustainable building practices. Another study was for O'Halloran & Kazeminejad (2019), who conducted a WBLCA for a mixed-use building in San Francisco, California, using the Tally® software. They compared three building systems: North American mass timber, Austrian mass timber, and steel, focusing on the total GWP and a breakdown by material type (mass timber, concrete, steel, and fireproofing) for each system. Their findings revealed that the North American mass timber system had the lowest overall GWP. In contrast, the steel system had the second highest GWP, showing an 8% increase compared to North American mass timber. The Austrian mass timber system exhibited the highest GWP, a 16% increase from the North American mass timber system. Analyzing the breakdown in terms of material type highlighted a nearly double CO_2 emission value in the mass timber material for the Austrian mass timber building, potentially due to larger members in this system and additional travel distance by boat. However, concrete emerged as the primary contributor to GWP and embodied energy, consistently representing at least half of the total emissions for each building system, regardless of the building system (Figure 2-22) (O'Halloran & Kazeminejad 2019).

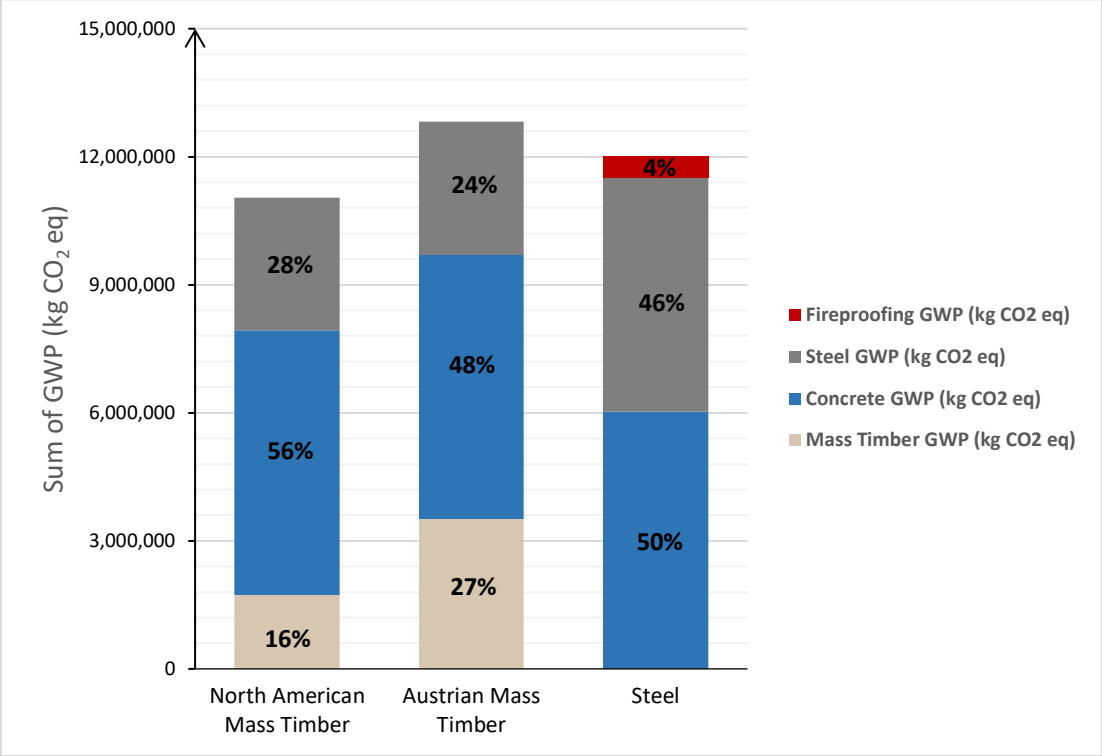


Figure 2-22: Comparison of GWP between North American mass timber building, Austrian mass timber building, and Austrian steel building, divided by the contribution of each material in each design.

In summary, the studies indicate that using mass timber products in buildings leads to a lower climate change impact compared to traditional building materials, mainly due to their low carbon footprint, greater reliance on renewable energy during production, and the carbon sequestration abilities of wood. However, mass timber can have a higher impact in certain specific categories. Despite these variations, conducting an LCA of buildings is essential for obtaining green building certifications, and incorporating wood materials contributes to earning certification points, underscoring the importance of sustainable materials in promoting environmentally responsible construction practices.

2.3 Problem Statement

A first-hand data of lumber products, encompassing material and energy inputs during manufacturing of lumber products, is notably necessary for conducting a cradle-to-gate LCA. Unfortunately, such a database is currently lacking, particularly in the Province of New Brunswick. The first study will address this problem and clarify the GWP impact (measured in CO_2 eq) associated with the lumber in all production stages.

Furthermore, a comprehensive understanding of the environmental benefits of full-mass timber structures or hybrid mass timber-steel structures, compared to conventional concrete or steel structures, is essential to accelerate the adoption of mass timber products in the building sector and support the achievement of carbon-neutral goals. Building on previous LCA studies of wood lumber products, the second LCA study of the actual mass timber hybrid design (Bakers Place Building) aims to provide comparative insights into the environmental benefits of these structures at the whole-building level for commercial

References

Abbas, D., & Handler, R. M. (2018). Life-cycle assessment of forest harvesting and transportation operations in Tennessee. Journal of Cleaner Production, 176, 512–520. https://doi.org/10.1016/j.jclepro.2017.12.080

Adhikari, S., & Ozarska, B. (2018). Minimizing environmental impacts of timber products through the production process "From Sawmill to Final Products". Environmental Systems Research, 7(1), 1–15. https://doi.org/10.1186/s40068-018-0114-x

Athena Sustainable Materials Institute. (n.d.). Publications. Retrieved May 08, 2024, from https://www.athenasmi.org/resources/publications/

Athena Sustainable Materials Institute. (2013). A Life Cycle Assessment of Cross-Laminated Timber Produced in Canada; Athena Sustainable Materials Institute: Ottawa, ON, Canada. Retrieved April 14, 2024, from https://www.athenasmi.org/wp-content/uploads/2013/10/CtoG-LCA-Canadian-CLT.pdf

Bare, J. (2011). TRACI 2.0: The tool for the reduction and assessment of chemical and other environmental impacts 2.0. Clean Technologies and Environmental Policy, 13(5), 687–696. https://doi.org/10.1007/s10098-010-0338-9

Berardi, U. (2017). A cross-country comparison of the building energy consumptions and their trends. Resources, Conservation and Recycling, 123, 230–241. https://doi.org/10.1016/j.resconrec.2016.03.014

Bergman, R. D., & Bowe, S. A. (2008). Environmental impact of producing hardwood lumber using life-cycle inventory. Wood and Fiber Science, 40(3), 448–458.

Bergman, R. D., & Bowe, S. A. (2010). Environmental impact of manufacturing softwood lumber in Northeastern and North Central United States. Wood and Fiber Science, 42, 67–78.

Bergman, R., Puettmann, M., Taylor, A., & Skog, K. E. (2014 a). The carbon impacts of wood products. Forest Products Journal, 64(7-8), 220-231. https://doi.org/10.13073/FPJ-D-14-00047

Bergman, R., Oneil, E., Puettmann, M., Eastin, I., & Ganguly, I. (2014b). Updating of U.S. wood product life-cycle assessment data for environmental product declarations. Forest Products Journal, 64(7–8), 232–242. https://doi.org/10.13073/FPJ-D-14-00046

Beyer, G., Defays, M., Fischer, M., Fletcher, J., & Munck, E. D. (2006). Tackle climate change: Use wood. Wood and Fiber Science, 42, 107–124.

Bowers, T., Puettmann, M. E., Ganguly, I., & Eastin, I. (2017). Cradle-to-gate life-cycle impact analysis of glued-laminated (glulam) timber: Environmental impacts from glulam produced in the US Pacific Northwest and Southeast. Forest Products Journal, 67(5-6), 368-380. https://doi.org/10.13073/FPJ-D-17-00030

Brandão, M., Levasseur, A., Kirschbaum, M. U., Weidema, B. P., Cowie, A. L., Jørgensen, S. V., ... & Chomkhamsri, K. (2013). Key issues and options in accounting for carbon sequestration and temporary storage in life cycle assessment and carbon footprinting. The International Journal of Life Cycle Assessment, 18, 230-240. https://doi.org/10.1007/s11367-012-0451-6

Chen, Cindy X., Pierobon, F., & Ganguly, I. (2019). Life Cycle Assessment (LCA) of Cross-Laminated Timber (CLT) produced in Western Washington: The role of logistics

and wood species mix. Sustainability (Switzerland), 11(5). https://doi.org/10.3390/su11051278

Comstock, G. L. (1975). Energy requirements for drying of wood products. Wood Residues as an Energy Source (Proc. No. P-75-13, pp. 8–12).

Curran, M. A. (2006). Life cycle assessment: principles and practice (No. EPA/600/R-06/060; p. 80). National Risk Management Research Laboratory, Cincinnati, OH.: U.S. Environmental Protection Agency (EPA).

Dionco-Adetayo, E. A. (2001). Utilization of wood wastes in Nigeria: a feasibility overview. Technovation, 21(1), 55-60.

European Committee for Standardization. (2011). Sustainability of construction works–Assessment of environmental performance of buildings–Calculation method (EN 15978). Brussels, Belgium: European Committee for Standardization.

Fnais, A., Rezgui, Y., Petri, I., Beach, T., Yeung, J., Ghoroghi, A., & Kubicki, S. (2022). The application of life cycle assessment in buildings: challenges, and directions for future research. The International Journal of Life Cycle Assessment, 27(5), 627-654.

Fuente, T.D., Athanassiadis, D., González-García, S., & Nordfjell, T. (2017). Cradle-to-gate life cycle assessment of forest supply chains: Comparison of Canadian and Swedish case studies. Journal of Cleaner Production, 143, 866-881.

Gu, C., Gu, H., Gong, M., Blackadar, J., & Zahabi, N. (2024). Comparison of using two LCA software programs to assess the environmental impacts of two institutional buildings. Sustainable Structures, 4(1), Article 000034. https://doi.org/10.54113/j.sust.2024.000034

Gu, C., Gu, H., Gong, M., & Blackadar, J. (2022). A case study on the impact of transportation of mass timber products on the cradle-to-gate LCA results for an institutional building. Recent Progress in Materials, 4(3), 1–14. https://doi.org/10.21926/rpm.2203014.

Gu, H., Nepal, P., Arvanitis, M., & Alderman, D. (2022). Carbon Impacts of Engineered Wood Products in Construction. IntechOpen. doi: 10.5772/intechopen.99193

Gu, H., & Bergman, R. (2018). Life cycle assessment and environmental building declaration for the design building at the University of Massachusetts. Forest Products Laboratory General Technical Report FPL-GTR-255. https://doi.org/10.2737/FPL-GTR-255.

Guinée, J. B., Heijungs, R., Huppes, G., Zamagni, A., Masoni, P., Buonamici, R., ... Rydberg, T. (2011). Life cycle assessment: Past, present, and future. Environmental Science and Technology, 45(1), 90–96. https://doi.org/10.1021/es101316v.

Guss, L. M. (1995). Engineered wood products: the future is bright. Forest Products Journal, 45(7, 8), 17.

Gong, M. (2022). Wood and engineered wood products: Stress and deformation. In M. Gong (Ed.), Engineered wood products for construction (pp. 1–20). IntechOpen. https://doi.org/10.5772/intechopen.101199

Gong, M. (2019). Lumber-based mass timber products in construction. In G. Concu (Ed.), Timber buildings and sustainability (pp. 27–46). IntechOpen. https://doi.org/10.5772/intechopen.83791

Hall, E. S. (2023). How to Calculate the Wood Carbon Footprint of a Building. Expanding the possibilities of wood building design. Think Wood. Retrieved February 11, 2024, from https://thinkwood-wordpress.s3.amazonaws.com/wp-content/uploads/2020/08/22161047/AR0920_CEU_THINKWOOD_20210527.pdf

fs.usda.gov/treesearch: https://doi.org/10.2737/FPL-GTR-255

Harte, A. M. (2017). Mass timber – The emergence of a modern construction material. Journal of Structural Integrity and Maintenance, 2(3), 121-132.

Hauschild, M. Z., & Huijbregts, M. A. (2015). Introducing life cycle impact assessment. In Life cycle impact assessment (pp. 1–16). Springer.

Hussain, M., Zaidi, S. M. H., Malik, R. N., & Sharma, B. D. (2014). Greenhouse gas emissions from the production chain of a cigarette manufacturing industry in Pakistan. Environmental Research, 134, 81-90.

IES. (2024). Embodied carbon vs operational carbon. Retrieved from https://www.iesve.com/discoveries/view/45462/embodied-carbon-vs-operational-carbon

International Organization for Standardization. (2006a). Environmental management — Life cycle assessment — Principles and framework. (ISO Standard No: 14040: 2006) Retrieved from https://www.iso.org/standard/37456.html

International Energy Agency. (n.d.). IEA Bioenergy FAQs: Biogenic CO_2 emissions from woody biomass. Retrieved April 11, 2024, from https://www.ieabioenergy.com/iea-publications/faq/woodybiomass/biogenic-co2/

Jensen, A. S. (2020). Mass timber solutions for eight-story mixed-use buildings: A comparative study of GHG emissions. Retrieved January 29, 2024, from www.preprints.org: https://www.preprints.org/manuscript/202007.0175/v2

Kelley, S., Gustafson, R., Puettmann, M., Oneil, E., Lippke, B., Morales-Vera, R., ... & Mason, L. (2020). Carbon cycling, environmental & rural economic impacts of collecting & processing specific woody feedstocks in biofuels (No. DOE-CORRIM-0002992-1). Consortium for Research on Renewable Industrial Materials (CORRIM), Corvallis, OR (United States).

Lippke, B., Wilson, J., Meil, J., & Taylor, A. (2010). Characterizing the importance of carbon stored in wood products. Wood and Fiber Science, 42, 5–14. https://wfs.swst.org/index.php/wfs/article/view/14

Mahalle, L. (2010). A Cradle-to-Gate Life Cycle Assessment of Canadian Hardwood Lumber. FPInnovations,Vancouver. https://library.fpinnovations.ca/en/permalink/fpipub41700

Matthews, H. S., Hendrickson, C. T., & Matthews, D. H. (2014). Life cycle assessment: Quantitative approaches for decisions that matter. https://www.lcatextbook.com/

Meil, J., Bushi, L., Garrahan, P., Aston, R., Gingras, A., & Elustondo, D. (2009). Status of energy use in Canadian wood products sector. Natural Resources Canada, Ottawa. https://cfs.nrcan.gc.ca/publications?id=30671

Milota, M. (2015). Life cycle assessment for the production of Pacific Northwest softwood lumber. CORRIM Final Report, Module B. https://corrim.org/wp-content/uploads/Module-B-PNW-Lumber.pdf

Milota, M. R., West, C. D., & Hartley, I. D. (2005). Gate-to-gate life-cycle inventory of softwood lumber production. Wood and Fiber Science, 37(4), 47–57. https://wfs.swst.org/index.php/wfs/article/view/1004

Milota, M., & Puettmann, M. E. (2017). Life-cycle assessment for the cradle-to-gate production of softwood lumber in the Pacific Northwest and Southeast regions. Forest Products Journal, 67(5–6), 331–342. https://doi.org/10.13073/FPJ-D-17-00034

Miner, R. (2010). Impact of the global forest industry on atmospheric greenhouse gases (No. 159). Food and Agriculture Organization of the United Nations (FAO). https://www.fao.org/3/i1580e/i1580e00.pdf

Natural Resources Canada. (2019). Forest products and applications. Retrieved August 10, 2024, from: https://www.nrcan.gc.ca/forests/industry/products-applications/16834/

O'Halloran, S., & Kazeminejad, Y. (2019). Whole building life cycle assessment (WBLCA) of mass timber systems: European vs North American mass timber vs steel. https://scholarsbank.uoregon.edu/xmlui/handle/1794/25200

Ormazabal, M., Jaca, C., & Puga-Leal, R. (2014). Analysis and comparison of life cycle assessment and carbon footprint software. Advances in Intelligent Systems and Computing, 281, 1521–1530. https://doi.org/10.1007/978-3-642-55122-2_131

Petersen, A. K., & Solberg, B. (2003). Substitution between floor constructions in wood and natural stone: comparison of energy consumption, greenhouse gas emissions, and costs over the life cycle. Canadian Journal of Forest Research, 33(6), 1061-1075.

PRe Consultants. (2012). SimaPro7 life-cycle assessment software package, version 7.3.2. Amersfoort, The Netherlands. Retrieved 24 September, 2024, from http://www.pre-sustainability.com.

Prentice, I. C., Farquhar, G. D., Fasham, M. J. R., Goulden, M. L., Heimann, M., Jaramillo, V. J., et al. (2001). The carbon cycle and atmospheric carbon dioxide. In J. T. Houghton et al. (Eds.), Climate change 2001: The scientific basis. Cambridge University Press. (pp. 183–237).

Puettmann, M. E. (2022). Carbon Analysis of Wood Composite Panels. Forest Products Journal, 72(2), 112–115. https://doi.org/10.13073/fpj-d-22-00010

Puettmann, M., Oneil, E., Wilson, J., & Johnson, L. (2013). Cradle to gate life cycle assessment of engineered I-joists production from the Pacific Northwest. Consortium for Research on Renewable Industrial Materials (CORRIM).

Puettmann, M. E., & Lippke, B. (2012). Woody biomass substitution for thermal energy at softwood lumber mills in the US Inland Northwest. Forest Products Journal, 62(4), 273-279.

Puettmann, M. E., Wagner, F. G., & Johnson, L. (2010 a). Life cycle inventory of softwood lumber from the inland northwest US. Wood and Fiber Science, 42, 52–66.

Puettmann, M. E., Bergman, R., Hubbard, S., Johnson, L., Lippke, B., Oneil, E., & Wagner, F. G. (2010b). Cradle-to-gate life-cycle inventory of US wood products production: CORRIM Phase I and Phase II products. Wood and Fiber Science, 42(Suppl. 1), 15–28.

Puettmann, M. E., & Wilson, J. B. (2007). Life-cycle analysis of wood products: Cradle-to-gate LCI of residential wood building materials. Wood and Fiber Science, 37, 18–29.

Puettmann, M. E., & Wilson, J. B. (2005). Gate-to-gate life-cycle inventory of glued-laminated timbers production. Wood and Fiber Science, 99-113.

Ritter, M. A., Skog, K., & Bergman, R. D. (2011). Science supporting the economic and environmental benefits of using wood and wood products in green building construction (p. 9). Washington, DC, USA: United States Department of Agriculture, Forest Service, Forest Products Laboratory.

Sahoo, K., Bergman, R., Alanya-Rosenbaum, S., Gu, H., & Liang, S. (2019). Life cycle assessment of forest-based products: A review. Sustainability, 11(17), 4722. https://doi.org/10.3390/su11174722

Sahoo, K., Bergman, R., & Runge, T. (2021). Life-cycle assessment of redwood lumber products in the US. The International Journal of Life Cycle Assessment, 26, 1702-1720.

Sathre, R., & Gustavsson, L. (2011). Time-dependent climate benefits of using forest residues to substitute fossil fuels. Biomass and Bioenergy, 35(7), 2506-2516.

Sathre, R., & O'Connor, J. (2010). A synthesis of research on wood products and greenhouse gas impacts 2nd edition (Technical Report No. TR-19R). FPInnovations.

Sharma, A., Saxena, A., Sethi, M., & Shree, V. (2011). Life cycle assessment of buildings: a review. Renewable and Sustainable Energy Reviews, 15(1), 871-875.

Sharma, B. D., & Wang, J. (2011). Status and potential of terrestrial carbon sequestration in West Virginia. In In: Fei, Songlin; Lhotka, John M.; Stringer, Jeffrey W.; Gottschalk, Kurt W.; Miller, Gary W., eds. Proceedings, 17th central hardwood forest conference; 2010 April 5-7; Lexington, KY; Gen. Tech. Rep. NRS-P-78. Newtown Square, PA: US

Department of Agriculture, Forest Service, Northern Research Station: 143-152. (Vol. 78, pp. 143-152).

Silva, D., Nunes, A. O., da Silva Moris, A., Moro, C., & Piekarski, T. O. R. (2017). How important is the LCA software tool you choose Comparative results from GaBi, openLCA, SimaPro and Umberto. In Proceedings of the VII Conferencia Internacional de Análisis de Ciclo de Vida en Latinoamérica, Medellin, Colombia (pp. 10-15).

Simonen, K. H. (2019). Life Cycle Assessment of Katerra's Cross-Laminated Timber (CLT) and Catalyst Building. Seattle: Carbon Leadership Forum and the Center for International Trade in Forest Products at the University of Washington.

Softwood Lumber Board & FPInnovations, Ben Romanchych Consulting. (2020). Mass Timber Outlook. Retrieved from: https://softwoodlumberboard.org/wp-content/uploads/2021/03/SLB-Mass-Timber-Outlook-2021-Final-Condensed.pdf.

Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K. B., Tignor, M., & Miller, H. L. (Eds.). (2007). Climate change 2007: The physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press. Retrieved March 12, 2024, from https://www.ipcc.ch/site/assets/uploads/2018/02/ar4-wg1-frontmatter-1.pdf

Stocker, T. F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S. K., Boschung, J., Nauels, A., Xia, Y., Bex, V., & Midgley, P. M. (Eds.). (2013). Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press. Retrieved

March 12, 2024, from https://www.ipcc.ch/site/assets/uploads/2017/09/WG1AR5_Frontmatter_FINAL.pdf

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(May), 172–177. https://doi.org/10.1016/j.procir.2017.11.121

Think Wood. (n.d.). Carbon source to carbon sink: Redesigning the built environment for climate change. https://www.thinkwood.com/blog/carbon-source-to-carbon-sink-redesigning-the-built-environment-for-climate-change

Wilson, J. B., & Dancer, E. R. (2005a). Gate-to-gate life-cycle inventory of I-joist production. Wood and Fiber Science, 37(85-98).

Wilson, J. B., & Dancer, E. R. (2005b). Gate-to-gate life-cycle inventory of laminated veneer lumber production. Wood and Fiber Science, 37(2), 114-127.

Wilson, J. B., & Sakimoto, E. T. (2005). Gate-to-gate life-cycle inventory of softwood plywood production. Wood and Fiber Science, 37(4), 58–73.

3 Case Study on the Cradle-to-Gate Life Cycle Assessment of Softwood Lumber Production in New Brunswick, Canada

Abstract

The construction sector increasingly emphasizes renewable materials like wood from sustainably managed forests due to wood's low embodied carbon and carbon storage potential, contributing to climate change mitigation. This study applies life cycle assessment (LCA) to evaluate the environmental impact of softwood lumber manufacturing in New Brunswick, Canada. Data were gathered from a local softwood sawmill through survey questionnaires and on-site visits, capturing details on raw material extraction, production processes, and fuel sources used to power the sawmill. A life-cycle inventory (LCI) was developed using mass allocation for primary products and co-products such as chips and sawdust. The LCA software SimaPro, with the North American impact method TRACI 2.1, was employed to conduct the life cycle impact assessment (LCIA) and analyze emissions. Results indicate that kiln-dried sawn lumber's greenhouse gas (GHG) emissions amount to 43 kg CO_2eq/m^3. Manufacturing processes with various unit processes, particularly kiln-drying, contributed over 60% of emissions. Carbon storage in the final lumber product was calculated at 204 kg, translating to approximately 748 kilograms of CO_2 eq/m^3—twelve times greater than its cradle-to-gate emissions. Thus, softwood lumber production demonstrated a negative Global Warming Potential (GWP) and functions as a carbon sink if used in long-life building constructions.

Keywords: Cradle-to-Gate, Greenhouse gas emission, Global Warming Potential, Life-cycle assessment, Softwood lumber, SimaPro

3.1 Introduction

The Intergovernmental Panel on Climate Change (IPCC) warns that a temperature increase beyond 2 degrees Celsius (ºC) could have irreversible consequences (Allen et al., 2018). Greenhouse gas (GHG) emissions are projected to raise global temperatures by 3.5 ºC by the century's end (Government of New Brunswick, 2018). In response to this urgency, it is necessary to have a deep understanding and good estimation of GHG emissions in order to help us determine the best actions to take to mitigate climate change. The building industry is a significant contributor to GHG emissions and consumes a large amount of natural resources arising from the manufacturing, transportation, installation, maintenance, and disposal of building materials, which refers to the embodied carbon. Globally, buildings account for 42% of carbon dioxide emissions, with 15% of embodied carbon originating from structural materials (Architecture 2030, n.d.). In response, many countries are committed to achieving the United Nations' Sustainable Development Goals (SDGs) (United Nations, 2023), leading to increased interest in materials with lower environmental impacts (Sahoo et al., 2021). Wood is a natural, renewable, reusable, and recyclable resource that can play a critical role in reducing negative impacts on the climate and environment when sourced from sustainably managed forests (Gong, 2022). The absorbed carbon during tree growth, remains stored in harvested wood products throughout their active service lives, delaying the release of sequestered carbon into the atmosphere (Gu et al., 2022), especially in structural materials with a lifespan of more than 50 years. This is a significant advantage over fossil fuel-intensive materials such as steel and concrete. At the end of their useful lives, wood products can be repurposed as biomass energy feedstock instead of being left to decay in landfills (Werner et al., 2005). However,

the environmental benefits of wood-based products must be appropriately quantified using relevant tools (Kutnar & Hill, 2017).

Life cycle assessment (LCA) is an internationally accepted, science-based method that assesses the environmental impact of a product or service by identifying and quantifying energy and materials used and emissions released to the environment at various stages during the life cycle of the product or service (ISO, 2006a, 2006b). LCA studies can either evaluate the entire product life cycle, commonly known as "cradle-to-grave," or focus on specific stages such as "cradle-to-gate" or "gate-to-gate (Puettmann et al., 2021). The cradle-to-gate LCA methodology used in this case study measures the environmental effect from the extraction of raw materials through production and until the product is ready to be shipped from the manufacturing site. The LCA process involves four major steps: defining the goal and scope, developing a life-cycle inventory (LCI), performing a life-cycle impact assessment (LCIA), and interpreting the results (ISO, 2006b).

Scientific documentation, such as the international standard ISO 14025, and environmental product declarations (EPD), provides verified data on the environmental performance of products and services to stakeholders such as architects and builders, consumers, regulating agencies, and policymakers (ISO, 2006c). Quantifying environmental performance for structural wood products such as lumber and EPDs of building products play a crucial role in the design of buildings to achieve green certifications. Products with validated EPDs are eligible for gaining credits from the Leadership in Energy and Environmental Design (LEED), Green Globes, and other green building rating systems, which can also be used to demonstrate compliance with other green building regulations.

Overall, utilizing wood products will help support the carbon neutrality goal by 2050 set by the Government of Canada. The specific objective of this study was to conduct a Cradle-to-Gate LCA analysis on the environmental impact of the softwood lumber products produced in one mill in New Brunswick, Canada. The overall objective of this study was to address the New Brunswick Climate Change Action Plan set by the Government of New Brunswick in 2016, specifically, Action Plan 21, which involves integrating wood products with favorable lifecycle evaluations, and Action Plan 61, which focuses on promoting wood as a renewable construction material through building codes and standards (Government of New Brunswick, 2016).

3.2 Methods

3.2.1 Goal and Scope of LCA

The goal of this study was to conduct an attributional LCA of the softwood lumber produced by a local mill in New Brunswick, Canada. The Life Cycle Inventory (LCI) of the material flow, energy use, and emissions on a per unit basis are collected from local producers to conduct the cradle-to-gate life cycle assessment of the softwood lumber products produced in the region. The scope of this study is described in detail in the following sections.

3.2.1.1 Functional Unit

Defining a reference unit for inputs and outputs is necessary for LCAs to properly evaluate environmental impacts. Since the cradle-to-gate stage rather than the whole life cycle (cradle-to-grave) was the focus of this study, a functional unit of 1 m^3 of planed dried softwood lumber was used as the reference. Thus, on the basis of this per functional unit basis, the LCI flows and the LCIA findings were provided.

3.2.1.2 System Boundary

This study considered the cradle-to-gate system boundary of softwood lumber, which begins with the material harvesting from the forest in the New Brunswick region (A1); resource and material transportation from suppliers to the mill (A2); and ends in the sawmill with various types of softwood lumber produced, packaged at the plant gate ready to be shipped (A3). The main unit processes in the manufacturing of softwood lumber were log yard, sawing, drying, and planing. Onsite heat energy generation is also included in the system boundary (Figure 3-1). Separating the LCI into these unit processes is necessary to ensure accurate allocation of burdens associated with the final product of softwood lumber and its co-products in each unit process. All allocation was based on the mass of the products and co-products.

The system boundary doesn't include forest operations (growing seedlings in a nursery, planting the seedlings), managing the forest, such as thinning and fertilization. The only first-hand data reported related to the A1 (resource extraction) was final harvesting with the logs brought to a forest landing.

Apart from producing heat on-site, the system's boundaries also included the extraction, processing, and delivery of purchased primary fuels, such as diesel, and primary fuels needed for generating electricity. The significant ancillary materials (e.g., hydraulic fluids, motor oils, greases, plastic strapping, lumber wrap) were also included within the system boundary.

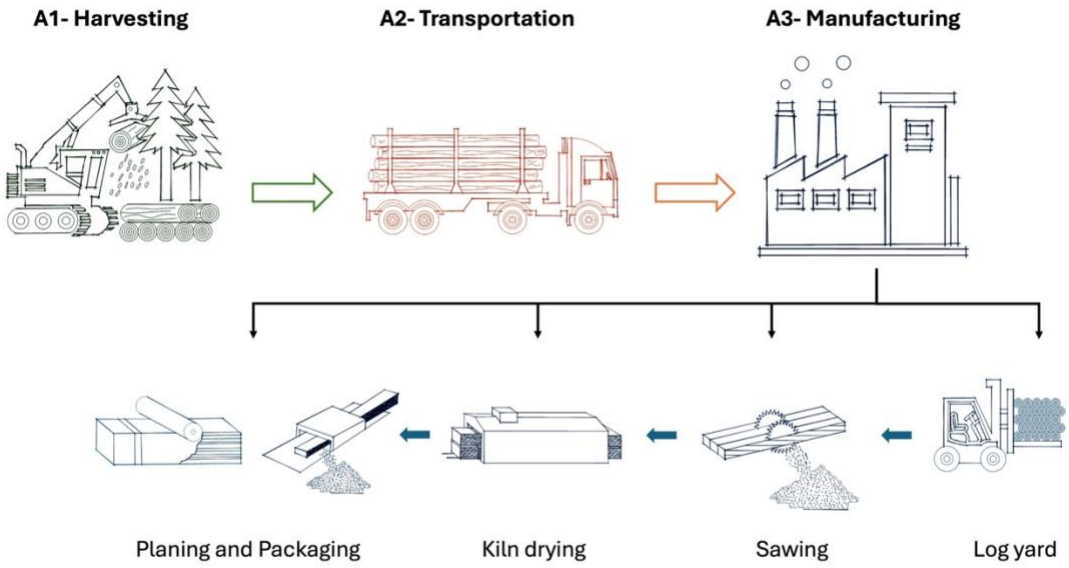


Figure 3-1: Illustration of the manufacturing processes for producing softwood lumber in New Brunswick, Canada.

3.2.2 Inventory Approach

Primary data such as the annual energy and material consumption were collected directly from the logging company and the large-scale softwood mill, both based in New Brunswick, Canada. These data were used to build the LCI of the softwood lumber manufacturing processes per functional unit basis, using an input/output process-based modeling approach for the LCI method, ensuring consistency and accuracy in the analysis. Mass balances of the material (ins and outs) for each unit operation were also calculated to develop the LCA model.

Secondary data of the LCIs for diesel, gasoline, propane, grid electricity mix, auxiliary materials, and transport were provided by the SimaPro software's DataSmart LCI database, which integrates and updates data from US LCI v.1.60 and Ecoinvent v.2.2 to appropriately represent U.S. operations (LTS, 2023).

3.2.2.1 Resource Extraction

In this study, the majority of harvested wood came from private forest landowner. The major softwood species harvested are Balsam Fir (*Abies balsamea*) (55%), Black Spruce (*Picea mariana*) (27%), and Jack Pine (*Pinus banksiana*) (8%) (Personal Communication with forestry company, 2024). Additionally, 10% of hardwoods, such as Birch (*Betula sp.*) and Maple (*Acer sp.*), were included in the mix of harvesting from the forest stands. The harvesting process is mainly mechanized, with only 1% involving manual chainsaw felling. Primary equipment used included feller bunchers and forwarders. Gasoline-powered trucks were used for log transportation in the woods. Overall, diesel and gasoline were the main

energy inputs for harvesting, while hydraulic fluid, lubricating fluid, motor oil, grease, and antifreeze served as ancillary materials to maintain harvesting equipment. The main product of this process was logs destined for lumber mills. The co-product, non-merchantable slash, is generally left at a landing and disposed, however, in this study, the survey respondents did not track the amount of residues generated during the operation. The energy and ancillary material used by the logging company that participated in the survey was calculated based on 1 m^3 of the roundwood harvested and shown in Table 3-1.

Table 3-11: LCI of Resource Extraction.

Resource	Inputs	Unit	Amount per m^3 of roundwood
Energy	Diesel fuel	litre	2.94
	Gasoline	litre	0.14
	Propane	litre	0.02
Ancillary Materials	Hydraulic fluid	litre	0.05
	Lubricating fluid	litre	0.08
	Motor oil	litre	0.02
	Greases	kg	0.0029

3.2.2.2 Transport of Logs from the Extraction Site to the Sawmill

Logs were transported by diesel trucks to the mills on public roads. The transportation value of 67 tonne-kilometer (tkm) was determined based on the weighted average distance traveled by logging trucks, which was 103 km (one way), and the green log density of 645 kg/m³, or 0.645 tonnes, at 67% moisture content (MC). Transportation was modeled as a stand-alone unit process rather than as an input to the logyard process (Table 3-2) to separately demonstrate the impacts from transportation in the overall impacts.

Table 3-12: Input/Output per m^3 of logs to the mill via transportation.

		Amount	Unit	Allocation
Output	Log at mill (including bark)	1	m^3	100%
Input	Log at forest road (including bark)	1	m^3	-
	Transport, combination truck	67	tkm	-

3.2.2.3 Product Manufacturing

This research separated the four primary unit operations of lumber manufacture into log yard, sawing, drying, and planing. A boiler was also included, which produced steam for drying. In 2022, the surveyed sample mill produced around 71,780 thousand board feet (MFBM) (169,402 m^3) of rough green lumber, in which about 10% left the system boundary in the sawing unit process and were sold as rough green lumber. Following that, the remaining rough green lumber was fed into the drying unit process, and all the rough dry lumber were planed and packaged to be shipped.

The lumber size profile produced by the sample mill was dominated by the production of 2×4 planed kiln-dried lumber, taking about 63.64% of the production. Table 3-3 displays the sizes, types and contribution of lumber produced in the surveyed sawmill in 2022.

Table 3-3 : The average size and type breakdown of softwood lumber produced in the surveyed sawmill in New Brunswick.

Size	Types of lumber	Contribution (%)
1 × 4	Rough green	2.80
2 × 4	Rough green	5.39
2 × 4	Surfaced dry	63.64
2 × 6	Rough green	0.90
2 × 6	Surfaced dry	25.57
1 × 3	Rough green	0.30
1 × 6	Rough green	0.02
2 × 3	Rough green	1.38
Total		100

Annual lumber product output (including rough green, rough dry, and planed dry) was reported by mill in MBFM. Forintek cubic metre conversion factors per MBFM lumber (Nielson et al., 1985), and mill data were employed to convert MBFM to m^3. A standard conversion rate from MBFM to cubic metres for rough green lumber was 2.36 m^3/MBFM, based on information from Nielson et al. (1985). The assumed conversion factor for rough dry lumber was 1.97 m^3/MBFM, derived from measuring sample shrinkage at a reported MC of 14%. Additionally, the sawmill provided a conversion factor of 1.62 m^3 per MBFM for planed dry lumber (final product). These ratios demonstrate that for 1.0 m^3 of planed dry lumber produced, 1.46 m^3 of rough green lumber and 1.22 m^3 of rough dry lumber were required.

3.2.2.3.1 Species, Moisture Content, and Specific Gravity of the Lumber Examined

The wood species in the production of softwood lumber include, black spruce (*Picea mariana*) (55%), Balsam Fir (*Abies balsamea*) (40%), Jack pine (*Pinus banksiana*) (5%). To determine the moisture content (MC) and specific gravity (SG) of the lumber, samples were gathered from the softwood sawmill, representing various species used in lumber manufacturing. These samples were then transported to the Wood Science and Technology Center (WSTC) at the University of New Brunswick, Fredericton, Canada, for research analysis. Following the ASTM D143 (ASTM International, 2023) standard, volume and weight of the samples were measured and physical properties of the samples, such as their specific gravity (i.e., relative density) and MC, were then determined. These properties are

essential for accurate conversion and analysis in the context of the LCA study, particularly to ensure precision in the mass balance.

In Table 3-4, a weighted-average green and dry specific gravity of 0.386 and 0.408, respectively were calculated based on the species distribution percentages obtained from the mill data and each individual species' specific gravity from measuring the green and dry samples of different species. Moreover, an initial MC 67% and a final weighted-average MC of 14% was determined for the green and dry lumber, respectively.

Table 3-4: Average physical properties of the species sawn into lumber.

Species	Contribution (%)	Specific gravity (green)	Specific gravity (dry)	Green MC[1] (dry basis) (%)	Dry MC[2] (dry basis) (%)
Black Spruce	55	0.404	0.427	58	13
Balsam Fir	40	0.359	0.378	83	15
Jack Pine	5	0.402	0.431	46	14
Weight average		0.386	0.408	67	14

[1] The moisture content of wood when freshly cut, expressed as a percentage of dry weight.

[2] The moisture content of wood after drying to stable moisture levels.

The oven dry (OD) weight of each coproduct, such as chips, sawdust, bark and shavings, was measured using the samples randomly collected from the sawmill, with an aim to determine the MC of the co-products. The MC values obtained for the co-products were as follows: green chips at 92, sawdust at 135, bark at 150, and dry shavings at 14.

3.2.2.3.2 Lumber manufacturing mass balance

Mass balance involves accounting for all material inputs and outputs within a defined system boundary, considering all processes. This is crucial for accurately evaluating the products and co-products based on the unit of the final product (e.g., 1 m^3 of planed dry lumber). Three primary stages of production (i.e., sawing, drying, and planing) and boiler operation and the entire value-chain process were considered to track material flow for the mass balance. All flow analyses of the product and coproducts in the process were determined on an OD weight basis, using the properties found in sample measurements and provided by the surveyed mill. Total of 1109.1 kg OD weight of incoming softwood logs including bark with a density of 645 kg/m^3 produced 1.0 m^3 of planed dry lumber with MC of 14%. Sawing produced 502 kg of rough green lumber, calculated by multiplying the green specific gravity (386 kg/m^3) by the volume (1.46 m^3) of rough green lumber used to produce 1 m^3 of planed dry lumber. Additionally, the rough green lumber that remained within the system boundary to produce the planed dry lumber was almost 89% of the total lumber production, which was also multiplied to determine that 502 kg of rough green lumber is required to produce 1 m^3 of planed dry lumber. For the co-products, the OD weight of the total value reported by mill was calculated per m^3 of planed dry lumber; the

drying process did not result in any loss of wood substance. Planing reduced the 502 OD kg of rough dry lumber to 408 OD kg of planed dry lumber, for roughly 19% reduction in mass. Boilers burned 61 OD kg of both green and dry mill residue (wood) fuel produced on-site (Table 3-5). Overall, a log excluding bark was reduced to almost 37% of its original mass in conversion to the final products of planed dry lumber. Table 5 provides a mass balance for a representative mill in New Brunswick's softwood lumber manufacturing sector.

Table 3-5: Mass balance for 1 m^3 of planed dry lumber (all values are converted to OD kg).

Material	Sawing process		Boiler	Drying process		Planing process		All Processes Combined		
	Input	Output	Input	Input	Output	Input	Output	Input	Output	Diff
Logs	998.1							998.1	0.0	-998.1
Green chips		346.2						0.0	346.2	346.2
sawdust		89.6	39.6					39.6	89.6	50.0
Bark	111.0	111.0						111.0	111.0	0.0
Rough green lumber		501.7		501.7				501.7	501.7	0.0
Rough green lumber, sold		60.7						0.0	60.7	60.7
Rough dry lumber					501.7	501.7		501.7	501.7	0.0
planed dry lumber							408.0	0.0	408.0	408.0
Dry Shavings			34.5				91.0	34.5	91.0	56.5
Sum	1109.1	1109.1	74.0	501.7	501.7	501.7	499.0	2186.0	2110.0	-76.7

3.2.2.3.3 Gate-to-Gate Energy and Material Input/Output

Material flows, energy use, and emissions data were normalized to the volume basis of 1 m^3 output at each unit process. As said, all the survey data for each unit process were converted to each functional unit: per m^3 of log for the log yard, per m^3 of rough-green lumber for the sawmill, per m^3 of rough-dry lumber for drying, and per m^3 of planed-dry lumber for planing.

3.2.2.3.4 Log yard

Unloading log trucks, scaling logs (reporting logs for volume in m^3), storing logs on decks, and moving logs to the sawmill were all of the activities included in the log yard process. Fuel type for equipment, such as loaders and forklifts used in the process of moving logs, are gasoline and diesel. There was also grease, antifreeze, hydraulic oil, and lubricant used in the equipment. In the log yard, a small quantity of electricity was used and considered in the calculation. The output at the log yard was the log with bark coming into the log yard, no wood material quantity changed in this unit process (Table 3-6).

Table 3-6: Unit process inputs/outputs for log yard activities to produce 1 m^3 of green logs.

		Amount	Unit	Allocation (%)
Output	Log at log yard (Including Bark)	1	m^3	100
Input	Log at mill (Including Bark)	1	m^3	
	Gasoline	0.00637	l	
	Diesel	0.787	l	
	Hydraulic fluid	0.0159	kg	
	Motor oils	0.00362	l	
	Grease	0.000265	kg	
	Antifreeze	0.0000748	l	
	Electricity	0.258	kWh	

3.2.2.3.5 Sawing (Production of Rough Green Lumber)

The sawing unit process involved several stages, including debarking logs, transforming logs into rough green lumber, sorting rough-green lumber by size, and stacking the lumber for drying. Key inputs included logs with bark, diesel and gasoline as fuels, and ancillary materials such as lubricant oil, hydraulic oil, grease, and antifreeze. Notably, the sawing process consumed the most electrical energy among all unit processes. The process generated outputs including green lumber at 45.2%, green chips at 31.2%, green sawdust at 8.1%, and bark at 10%. There was also 5.5% of the rough green lumber, which was sold and left the system boundary in the sawing unit process. Allocation of products and coproducts was based on oven-dry mass. While most wood residues were sold as coproducts, some were combusted as fuel for onsite heat generation to dry lumber. Table 3-7 summarizes the products and co-products outputs, as well as inputs required for the sawing process, which produces $1m^3$ of rough sawn green lumber in the New Brunswick softwood sawmill.

Table 3-7: Inputs/outputs for sawing unit process to produce 1 m^3 of rough green softwood lumber.

		Amount	Unit	Allocation (%)
Output	Rough green lumber	1	m^3	45.2
	Rough green sold	42	kg	5.5
	Green chips	237.64	kg	31.2
	Sawdust	61.5	kg	8.1
	Bark	76.19	kg	10.0
Input	Roundwood	2.21	m^3	
	Gasoline	0.00649	l	
	Diesel	0.936	l	
	Hydraulic fluid	0.0736	l	
	Motor oils	0.00246	l	
	Grease	0.00117	kg	
	Antifreeze	0.000254	l	
	Electricity	46.99	kWh	
	Lubricant fluid	0.142	l	
	Paint	0.00127	kg	

3.2.2.3.6 Kiln-Drying (Production of Rough Dry Lumber)

Rough-green stacked lumber had to be loaded into kilns to dry. Then the rough-dry stacked lumber would be unloaded from the kilns. These were the surveyed activities in the drying process. The primary inputs were rough green lumber, electricity and diesel/gasoline used, and thermal energy produced by the boiler. The mill under the survey used continuous kilns, which is more energy efficient to dry softwoods than batch kilns (Salin & Wamming, 2008). Rough dry lumber was the output of the drying process (Table 3-8). The softwood lumber is typically dried to a moisture content of 14%. In this surveyed sawmill, all the output rough-dried lumber would go to the planing process.

Table 3-8: Unit process inputs/outputs for kiln drying to produce 1 m^3 of rough dry softwood lumber.

		Amount	Unit	Allocation (%)
Output	Rough dry lumber	1	m^3	100
Input	Rough green lumber	1	m^3	
	Gasoline	0.000648	l	
	Diesel	0.0801	l	
	Hydraulic fluid	0.00367	l	
	Motor oils	0.000737	l	
	Grease	0.0000539	kg	
	Electricity	12.73	kWh	
	Paint	0.000380	kg	
	Heat, on-site boiler	1356	MJ	

3.2.2.3.7 Boiler Process (On-site Heat Production)

The combustion of wood in the boiler to generate heat was analyzed as a separate unit process within this survey. Also, water emissions from this process were reported based on the mill's water discharge test results. The boiler process primarily focused on producing heat energy for the kilns. The surveyed sawmill exclusively used wood-fuel boilers for supplying heat during the kiln-drying process, with no natural gas-fired alternatives. Wood fuel burned in the boiler is 100% from on-site produced material, comprising 56% sawdust and 46% planer shavings as inputs. Higher heating value (HHV) conversion was employed to represent the energy content of wood fuel combustion, assuming 20.9 MJ of energy produced per kg of OD wood. Table 3-9 shows the input and output of this unit process. Water emissions and a small amount of wood ash were reported as outputs from the mill's boiler process.

Table 3-9: Inputs/outputs for boiler Unit process producing onsite heat.

		Amount	Unit	Allocation (%)
Output	Heat, on site boiler	20.9	MJ	100
	Wood ash	0.00236	kg	
Input	Water, process, well	0.00446	kg	
	Sawdust	0.562	kg	
	Shavings	0.438	kg	
	Gasoline	0.0000100	l	
	Diesel	0.00123	l	
	Hydraulic fluid	0.0000567	l	
	Electricity	0.00214	kWh	
	Motor oil	0.0000114	l	
	Grease	0.000000831	kg	
	Antifreeze	0.000000156	l	
Emission to Water	BOD	0.0268	mg	
	Suspended solids	0.0803	mg	
	Chromium	0.00446	µg	
	Iron	10.437	µg	
	Aluminum	2.101	µg	
	Nickel	0.00446	µg	
	Lead	0.00357	µg	
	Zinc	0.0178	µg	
	Metal Ion	0.201	mg	

3.2.2.3.8 Planing (Production of Packaged Planed Dry Lumber)

The planing process involved several steps: unstacking rough dry lumber, planing the lumber, trimming, grading, sorting, stacking, strapping, and packaging the lumber, as well as transporting it within the planer mill to prepare for shipment. Inputs for this process included rough dry lumber, electricity, diesel, gasoline, lubricant oil, hydraulic oil, grease, antifreeze, plastic strapping and lumber wrap. The outputs were packaged planed dry lumber, sorted by type, size, and grade, as well as planer shavings (as shown in Table 3-10). This stage marks the final step in the surveyed manufacturing process. Some dry wood residue was burned on-site in boilers for energy, while some was sold as co-products. The planed dry lumber takes up 82% of the total mass of the products and co-products from this process, with shavings making up the remaining 18%. The lumber is bundled, banded with plastic strapping, and wrapped for shipping.

Table 3-10: Inputs/outputs for planing Unit process to produce 1 m^3 of planed dry softwood lumber.

		Amount	Unit	Allocation (%)
Output	Planed dry lumber	1	m^3	82
	Shavings	91	kg	18
Input	Rough dry lumber	1.22	m^3	
	Gasoline	0.00306	l	
	Diesel	0.378	l	
	Hydraulic fluid	0.0173	l	
	Motor oils	0.00348	l	
	Grease	0.000286	kg	
	Electricity	26	kWh	
	Plastic strapping	0.0741	kg	
	Lumber wrap	0.169	kg	
	Lubricant fluid	0.0501	l	
	Antifreeze	0.0000479	l	

3.2.2.4 Secondary Data Sources

Table 3-11 lists the secondary LCI data used in this modeling of the LCA study for raw material inputs, ancillary materials and packaging, transportation, fuels and energy for manufacturing.

Table 3-11: Material LCI data drawn from the DataSmart database (LTS, 2023). All data are for North America, except electricity (Canada), and reflect the year 2018.

Data	LCI Data Source
Diesel	US EI 2.2 (DataSmart2023): Diesel, combusted in Industrial equipment NREL/US U
Gasoline	US EI 2.2 (DataSmart2023): gasoline, combusted in industrial equipment/US
Propane	US EI 2.2 (DataSmart2023): Liquefied petroleum gas, combusted in industrial boiler/US
Electricity	Electricity mix, New Brunswick/CA U
Hydraulic fluid, Lubricant oil	US EI 2.2 (DataSmart2023): Lubricating oil, at plant/US- US-EI U
Motor oil, Greases	US EI 2.2 (DataSmart2023): Diesel, at refinery/l NREL /US
Antifreeze	US EI 2.2 (DataSmart2023): ethylene glycol, at plant/US - US-EI U
Paint	US EI 2.2 (DataSmart2023): Alkyd paint, white, 60% in H2O, at plant/US-US-EI U
Plastic strap	US EI 2.2 (DataSmart2023): Polyethylene, HDPE, granulate, at plant/ US- US-EI U
Lumber wrap	US EI 2.2 (DataSmart2023): Polypropylene resin, at plant NREL /RNA
Trucking	US EI 2.2 (DataSmart2023): Transport, combination truck, Diesel powered NREL/US U

3.3 Life Cycle Impact Assessment (LCIA)

Linking the LCI to potential impacts on the environment is the goal of the LCIA phase. SimaPro (v9.6.0.1) was used to model the LCA of this cradle-to-gate softwood lumber product system. Within SimaPro, all process data, including inputs and outputs were considered and modeled to represent each unit process. The midpoint impact categories for acidification, eutrophication, global warming, smog, and ozone depletion were all determined using the TRACI method (Bare et al., 2011), due to its characterization factors, which specifically designed to quantify environmental impacts in alignment with U.S. These factors ensure consistent, accurate assessments, producing results that are both scientifically valid and regionally relevant. Although the TRACI method addresses fossil fuel depletion on a global scale, it does not report primary energy use as an impact category. Therefore, the Cumulative Energy Demand (CED) method was also employed. CED calculates the total energy derived from all sources directly extracted from the earth, including natural gas, oil, coal, biomass, nuclear, and hydropower. This total primary energy is further categorized into non-renewable fossil, nuclear and renewable energies.

Cradle-to-gate environmental performance results for all reporting indicators are listed in Table 12 for softwood lumber produced in the New Brunswick region. It showed the values for A1-resource extraction, A2-transportation, and A3-softwood lumber production. About 62% of the CO_2 eq (GWP) came from lumber production process (26.6 kg CO_2 eq/m^3 of softwood lumber). Within the A3 stage, 37% of GWP impact was from the lumber drying, which was the highest contribution. Followed by that is the sawing unit process with 28%, due to a notable electricity usage in this stage. Planing and log yard unit processes contributed 25% and 10%, respectively. 23% of the GWP impact resulted from the

harvesting operations with 10 kg CO_2 eq per m^3 of softwood lumber product. Transportation, which is primarily the transport of logs to the sawmill, was 6.34 kg CO_2 eq/m^3 of softwood lumber or 15% of the cradle-to-gate GWP impact.

Lumber production (A3) represented the highest impacts for the ozone depletion, Acidification, Eutrophication and fossil fuel depletion environmental impact categories compared with the resource extraction (A1) and transportation (A2). However, resource extraction (A1) had the highest impact on the smog category, only surpassing the lumber production process (A3) by a very small margin.

Table 3-12 also provides the values of energy and resources. The total energy consumption was 2,377 MJ/m^3, with more than 50% of that being renewable energy consumption. Approximately 1,370 MJ/m^3 of renewable biomass energy was consumed, most of which came from the on-site combustion of wood for drying purposes (1,356 MJ/m^3). Fossil energy amounted to 610 MJ/m^3, primarily used for machinery, transportation, and electricity.

Table 3-12: Cradle-to-gate environmental performance of 1 m^3 planed dry softwood lumber based on mass allocation for New Brunswick, Canada.

	Environmental Indicator	Unit	Total	A1	A2	A3
Impact Category	Global Warming	kg CO_2 eq	43.02	10.06	6.34	26.62
	Acidification	kg SO_2 eq	0.35	0.13	0.035	0.18
	Eutrophication	kg N eq	0.063	0.01	0.0032	0.050
	Smog	kg O_3 eq	9.28	4.23	1.01	4.03
	Ozone Depletion	kg CFC-11 eq	2.34E-06	8.36E-08	1.06E-08	2.25E-06
	Fossil Fuel Depletion	MJ surplus	69.94	20.06	11.23	38.66
Energy Consumption	Total primary energy	MJ	2377.16	152.73	85.48	2138.94
	Non-renewable fossil	MJ	610.33	150.50	84.26	375.56
	Non-renewable nuclear	MJ	380.75	2.09	1.15	377.51
	Renewable biomass	MJ	1369.85	0.06	0.03	1369.77
	Renewables (solar, wind, hydro and geothermal)	MJ	16.23	0.09	0.04	16.10

Figure 3-2 shows contribution of the resource extraction and transportation stages and each unit process in the manufacturing stage (A3) separately in the six midpoint environmental impacts for the cradle-to-gate life-cycle stages of softwood lumber production. Compared with all stages and unit processes, harvesting had the largest impact in smog, acidification and fossil fuel depletion with 46, 37 and 29%, respectively. For the global warming impact, the harvesting process contributed equally to the kiln drying unit process, each at 23%. This was followed by the sawing unit process at 17%, and the planing unit process and transportation (A2), both contributing 15%. The lowest global warming impact was attributed to the log yard unit process (6%). Moreover, sawing, planning, and drying caused most of the impact in the ozone depletion impact category with 33, 32 and 29%, respectively.

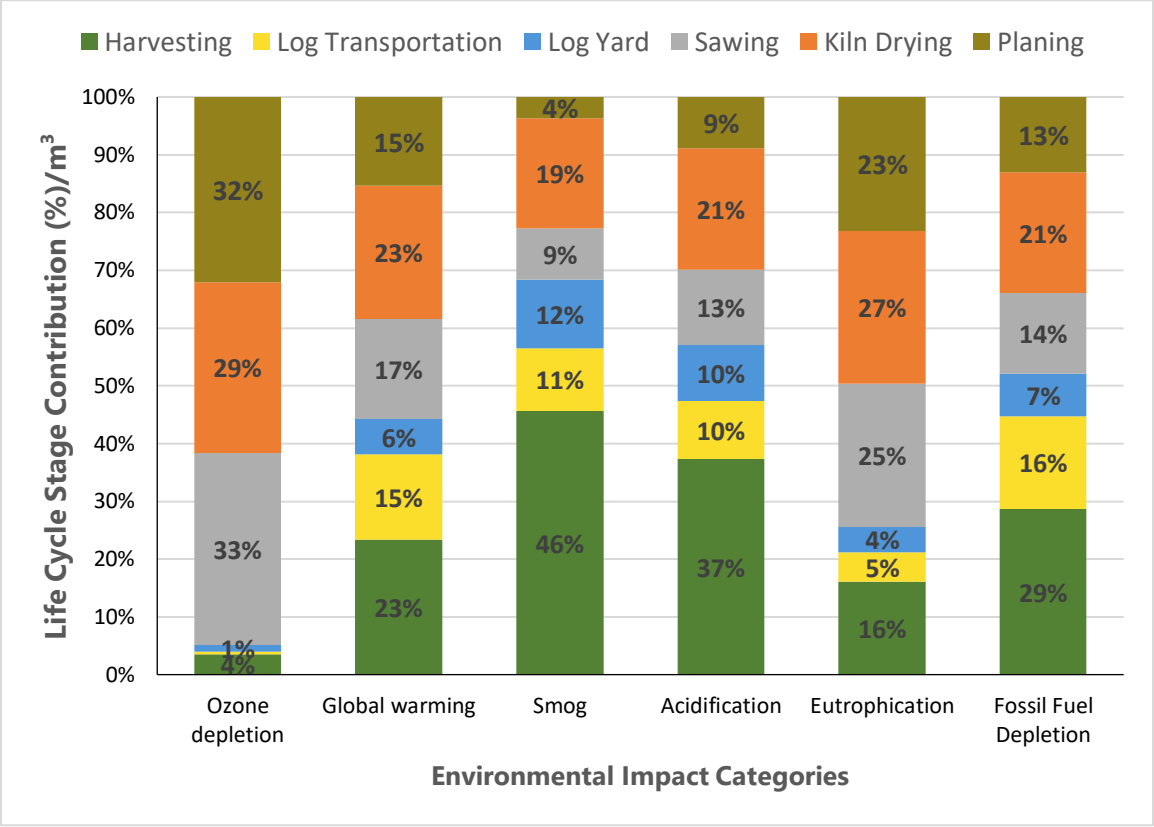


Figure 3-2: Contribution of unit processes in environmental impacts for the cradle-to-gate life-cycle stages of 1 m^3 planed dry softwood lumber produced at one sawmill in New Brunswick, Canada.

3.4 Biogenic Carbon

Softwood lumber in service stores biogenic carbon during its life. The production of 1 m^3 of softwood lumber in one sawmill in New Brunswick emitted a total of 43 kg CO_2 eq fossil-based carbon in the value chain. The biogenic carbon stored in 1 m^3 (408 OD kg) of planed dry softwood lumber amounts to 204 kg of carbon, assuming 50% of mass in wood is carbon. When considering the CO_2/C molecular weight ratio 44/12, the biogenic carbon in the 1 m^3 softwood lumber product equates to 748 kg of CO_2 stored, which is approximately 17 times higher than the fossil carbon emitted during the cradle-to-gate value chain production. This suggests that use of lumber/wood in construction is beneficial to the environment by keeping carbon sequestered over the life span of a building, thereby contributing to climate change mitigation.

3.5 Discussion

In 2018, the Athena Institute released a LCA report on the lumber produced in Eastern Canada using SimaPro LCA tool, covering Ontario, Quebec, and one sawmill in New Brunswick (Athena Sustainable Materials Institute, 2018). The primary data were collected based on 2015 calendar year production of 4 mills and was weighted and aggregated with data for 10 other facilities based on the 2006/2007 data in order to increase the overall sample size. The report mostly was relied on secondary sources as assumption for the specific gravity, MC, and other wood properties. In this study all the properties of the wood were determined by actual measurement of samples from the surveyed mill. The measured values were found to be very close to the previous study.

Table 3-13 shows the comparison between the previous study by Athena Sustainable Materials Institute (2018) and this study (2022 data). The total GWP in the current study increased by 10% compared to the previous report, primarily due to a 30% higher GWP impact during the manufacturing stage. This study reported no usage of gas in the boiler, whereas the previous report indicated that approximately 0.8 m^3 of natural gas was used per m^3 of planed dry lumber. This saving was compensated by the higher electricity usage per m^3 of planed dry lumber in the production stage of this study (86 kWh) compared to the previous one (71 kWh/m^3). Additionally, all the electricity used in this surveyed sawmill was purchased, with no on-site renewable electricity generation reported.

Moreover, there was a 5% decrease in total primary energy use in the production of softwood lumber in this study (2,377 MJ/m^3) compared with the previous study (2,509 MJ/m^3 using the higher heating value of all fuel–energy inputs) (Athena Sustainable Materials Institute, 2018). The use of non-renewable fossil energy also had a slight increase with almost 2% in the current study bringing it to 610 MJ/m^3. However, the renewable biomass energy consumption was 22% lower in the current study, which is mainly due to lower wood OD kg combustion on-site to generate energy in this study.

The environmental impacts of a product are significantly influenced by the technology and the fuel types used in regional electricity generation. The evidence was shown by the study of comparisons of wood product manufacturing across different geographic locations (Puettmann & Wilson, 2005). This study found a 40% increase in non-renewable energy use and a 23% decrease in renewable energy use compared to the Athena Institute report, which represents the averaged data from various eastern Canadian provinces. Specifically, non-renewable nuclear energy usage increased by 248% in this study, while renewable

energy sources (such as solar, wind, and hydro) decreased by 63%. These differences were primarily due to New Brunswick's high reliance on nuclear power at 38% and low reliance on hydro at 20%, in contrast to other eastern provinces like Quebec, which relied 94% on hydropower (LTS, 2023).

A study by Siddiqui & Dincer (2017) analyzed the environmental impacts of nuclear, wind, and hydropower plants in the Province of Ontario, Canada, using a cradle-to-grave LCA and CML 2001 methods. They found that wind power had the highest eutrophication impact, while hydropower had substantially lower impacts. Despite similar wind and hydropower percentages in New Brunswick and Ontario's electricity profile (11 and 23%, respectively) (LTS, 2023; Siddiqui & Dincer, 2017), Quebec's near-total reliance on hydropower led to lower eutrophication impacts in the Athena institute's LCA study on lumber produced in eastern Canada (Athena Sustainable Materials Institute, 2018). In contrast, this study's focus on New Brunswick resulted in a 158% increase in eutrophication impacts. Overall, these differences are attributed to variations in raw material usage and energy sources across different regions. This underscores the importance of regionalizing LCI data to accurately capture local environmental impacts.

Table 3-13: LCIA comparison between previous data (Athena Sustainable Materials Institute, 2018, based on different region in eastern Canada) and current study data (based on New Brunswick industry surveys in 2022) on softwood lumber production.

Impact Category	Units	Current Study	Past Study	Percent change (%)
Global warming potential	kg CO_2 eq	43.02	39.06	10
Acidification	kg SO_2 eq	0.35	0.45	-22
Eutrophication potential	kg N eq	0.064	2.46E-02	158
Smog potential	kg O_3 eq	9.28	10.46	-11
Ozone depletion potential	kg CFC11eq	2.34E-06	1.39E-06	69
Total primary energy	MJ	2377.16	2508.8	-5
Non-renewable fossil	MJ	610.33	598.99	2
Non-renewable nuclear	MJ	380.75	109.33	248
Renewable biomass	MJ	1369.85	1756.26	-22
Renewables (solar, wind, hydro and geothermal)	MJ	16.23	44.22	-63

3.6 Conclusions

This study conducted a cradle-to-gate LCA of planed kiln-dried softwood lumber from a single sawmill in New Brunswick, using both primary production data and secondary material/energy LCI data from the DataSmart database. The following conclusions were drawn from the study:

- 77% of overall energy consumption was attributed to the lumber production, with sawing and kiln drying contributing the most to GWP within the production stage.
- Harvesting had significant impacts on smog formation (46%), acidification (37%), and fossil fuel depletion (29%).
- Renewable energy, primarily woody biomass, accounted for 58% of total energy consumption, while 42% came from non-renewable sources. Transportation and harvesting contributed 14 and 25%, respectively, to non-renewable fuel usage.

To further reduce the overall use of non-renewable energy and the associated GWP impacts, increasing the use of renewable biomass sources, such as mill or forest residues, directly and indirectly, especially throughout the production stages, would be recommended. Utilizing these residues could provide a sustainable energy alternative throughout the production stages, thereby reducing reliance on fossil fuels, and minimize the environmental footprint of softwood lumber production in New Brunswick. Implementing these strategies could greatly contribute to more sustainable industry practices.

References

Allen, M. R., et al. (2018). Framing and context. In V. Masson-Delmotte et al. (Eds.), Global warming of 1.5°C. An IPCC special report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty (pp. 49-92). Cambridge University Press. https://doi.org/10.1017/9781009157940.003

Architecture 2030 (n.d.) Why the built environment? Retrieved July 15, 2024, from https://www.architecture2030.org/why-the-built-environment/

ASTM International (2023) Standard test methods for small clear specimens of timber (ASTM D143-14). West Conshohocken, PA: ASTM International. https://doi.org/10.1520/D0143-14

Athena Sustainable Materials Institute. (2018). A Cradle-to-Gate Life Cycle Assessment of Eastern Canadian Surfaced Dry Softwood Lumber. Retrieved January 15, 2023, from https://www.athenasmi.org/wp-content/uploads/2018/07/CtG-LCA-of-Eastern-Canadian-Surfaced-Dry-Softwood-Lumber.pdf.

Bare, J. (2011). TRACI 2.0: The tool for the reduction and assessment of chemical and other environmental impacts 2.0. Clean Technologies and Environmental Policy, 13(5), 687–696. https://doi.org/10.1007/s10098-010-0338-9

Frischknecht, R., Jungbluth, N., Althaus, H. J., Doka, G., Dones, R., Hischier, R., Hellweg, S., Humbert, S., Margni, M., Nemecek, T., & Spielmann, M. (2007). Implementation of

Life Cycle Impact Assessment Methods: Data v2.0. ecoinvent report No. 3. Swiss Centre for Life Cycle Inventories, Dübendorf, Switzerland.

Gong, M. (2022). Wood and engineered wood products: Stress and deformation. In M. Gong (Ed.), Engineered wood products for construction (pp. 1–20). IntechOpen. https://doi.org/10.5772/intechopen.101199

Government of New Brunswick. (2018). Climate Change Act. Retrieved May 22, 2024, from https://laws.gnb.ca/en/pdf/as/2018,%20C.11.pdf

Government of New Brunswick. (2016). Transitioning to a low-carbon economy: New Brunswick's climate change action plan. Government of New Brunswick. Retrieved June 23, 2024, from https://www2.gnb.ca/content/dam/gnb/Departments/env/pdf/ClimateClimatiques/TransitioningToALowCarbonEconomy.pdf

Gu, H., Nepal, P., Arvanitis, M., & Alderman, D. (2022). Carbon Impacts of Engineered Wood Products in Construction. IntechOpen. https://doi.org/10.5772/intechopen.99193

International Organization for Standardization. (2006a). Environmental management—Life cycle assessment—Principles and framework (ISO Standard No. 14040:2006). https://www.iso.org/standard/37456.html

International Organization for Standardization. (2006b). Environmental management—Life cycle assessment—Requirements and guidelines (ISO Standard No. 14044:2006). https://www.iso.org/standard/38498.html

International Organization for Standardization. (2006c). Environmental labels and declarations—Type III environmental declarations—Principles and procedures (ISO Standard No. 14025:2006). https://www.iso.org/standard/38131.html

Kutnar, A., & Hill, C. (2017). Life cycle assessment–opportunities for forest products sector. BioProducts Business, 2(6), 52-64. https://biobus.swst.org/index.php/bpbj/article/view/10

LTS (2023) DataSmart Life Cycle Inventory. Retrieved September 20, 2023, from https://longtrailsustainability.com/software/datasmart-life-cycle-inventory/

Nielson, R. W., Dobie, J., & Wright, D. M. (1985). Conversion factors for the forest products industry in Western Canada (Special Publication No. SP-24). Vancouver, BC: Forintek Canada Corp.

Puettmann, M., Pierobon, F., Ganguly, I., Gu, H., Chen, C., Liang, S., Jones, S., Maples, I., & Wishnie, M. (2021). Comparative LCAs of conventional and mass timber buildings in regions with potential for mass timber penetration. Sustainability, 13(24), 13987. https://doi.org/10.3390/su132413987

Puettmann, M. E., & Wilson, J. B. (2005). Life-cycle analysis of wood products: Cradle-to-gate LCI of residential wood building materials. Wood and Fiber Science, 37(5), 18–29.

Sahoo, K., Bergman, R., & Puettmann, M. (2021). Cradle-to-gate life-cycle assessment of North American laminated strand lumber production (Research Paper FPL–RP–710). U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. Retrieved September 18, 2023, from https://www.fpl.fs.usda.gov/documnts/fplrp/fpl_rp710.pdf

Salin, J. G., & Wamming, T. (2008). Drying of timber in progressive kilns: Simulation, quality, energy consumption, and drying cost considerations. Wood Material Science & Engineering, 3(1–2), 12–20. https://doi.org/10.1080/17480270802561003

Siddiqui, O., & Dincer, I. (2017). Comparative assessment of the environmental impacts of nuclear, wind, and hydro-electric power plants in Ontario: A life cycle assessment. Journal of Cleaner Production, 164, 848–860. https://doi.org/10.1016/j.jclepro.2017.06.237

United Nations. (2023). Take urgent action to combat climate change and its impacts. Retrieved September 19, 2024, from https://sdgs.un.org/goals/goal13#progress_and_info

Werner, F., Taverna, R., Hofer, P., & Richter, K. (2005). Carbon pool and substitution effects of an increased use of wood in buildings in Switzerland: First estimates. Annals of Forest Science, 62(8), 889–902. https://doi.org/10.1051/forest:2005080

4 Case Study on the Cradle-to-Gate Life Cycle Assessment of Hardwood Lumber Production in New Brunswick

Abstract

This case study conducted a cradle-to-gate life cycle assessment (LCA) for the production of hardwood lumber in New Brunswick, Canada, evaluating environmental impacts from raw material extraction to the point where lumber exited the mill as rough green, the primary input for manufacturing pallets and railway ties. Data on annual production, material flow, and energy use for harvesting and sawmilling were gathered through survey questionnaires and on-site visits. The life cycle inventory (LCI) was developed in SimaPro software, the life cycle impact assessment (LCIA) was conducted using the North American TRACI method to quantify impact categories, and the Cumulative Energy Demand (CED) method was employed to analyze the total energy consumption. It was found rough green hardwood lumber production emitted approximately 41 kg CO_2 eq/m^3 (excluding biogenic carbon storage), with manufacturing accounting for 42% of total emissions and consuming 736 MJ/m^3 of total energy, 98% of which came from non-renewable sources. The carbon stored in lumber was 975 CO_2 eq/m^3, 24 times greater than its cradle-to-gate emissions, highlighting its significant environmental benefit. Future research will aim to do a cradle-to-grave LCA on hardwood production by including drying and planning and increase the number of sawmill samples.

Keywords: Biogenic Carbon, Carbon Emission, Cradle-to-Gate Life Cycle Assessment, Cumulative Energy Demand, Environmental Impact, Hardwood Lumber Production

4.1 Introduction

The growing urgency to address climate change has placed carbon neutrality at the priority of global environmental goals (Ye et al., 2024). Carbon neutrality refers to the state in which the net amount of carbon dioxide (CO_2) or other greenhouse gases (GHGs) emitted into the atmosphere is balanced by an equivalent amount being removed or offset, resulting in zero net emissions and minimizing the impact on the climate. Wood, as a natural, renewable, reusable, and recyclable resource, plays a critical role in reducing environmental impacts and contributing to carbon neutrality (Gong, 2022). During growth, trees sequester carbon dioxide from the atmosphere, storing it as carbon within the wood. This stored carbon remains in wood products throughout their active service lives until disposal or combustion (Grossi et al., 2023). In the context of wood, carbon neutrality assumes that carbon emissions from the combustion or decomposition of wood biomass—classified as biogenic carbon—are part of the natural carbon cycle and are offset by the carbon absorbed by newly planted trees. However, achieving true carbon neutrality for wood requires consideration of carbon emissions across the entire lifecycle of wood products, including those generated during production processes such as harvesting, sawing, drying, and transportation. Additionally, sustainable forestry practices, forest regrowth, and proper end-of-life management of wood products are essential to maximize the duration of carbon storage (Hubbard et al., 2020; Gu et al., 2022; Hemmati et al., 2024). The Government of New Brunswick, Canada, has set regulations and policies to reduce GHG emissions, which are, under the RCP 8.5 scenario reported in the IPCC Fifth Assessment Report (AR5), projected to increase global temperatures by approximately 3.5°C by the end of the century (Government of New Brunswick, 2018; IPCC, 2014).

These regulations support the goal of carbon neutrality by 2050 set by the Government of Canada as well as commitment to achieving the United Nations' Sustainable Development Goals (SDGs) (United nations, 2023). The Action Plan outlines 118 strategies to promote sustainability across various sectors, including construction. Among these, Action Plan 21 integrates wood products with favorable life cycle assessment (LCA), recognizing their potential to reduce environmental impacts, while Action Plan 61 promotes wood as a renewable construction material through updated building codes and standards (Government of New Brunswick, 2016). Forest landowners and wood product manufacturers must adapt to strict environmental regulations and enhance their market competitiveness. By prioritizing sustainable practices and using renewable materials like wood from managed forests, industry can reduce the environmental footprint and increase opportunities for green marketing (Puettmann et al, 2010). However, the environmental benefits of wood-based products must be appropriately quantified using relevant tools (Kuntar & Hill, 2017). LCA is an internationally accepted, science-based method that assesses the environmental impact of a product or service by identifying and quantifying energy and materials used and emissions released to the environment at various stages during the life cycle of a product or service (ISO 14040, 2006; ISO 14044, 2006). The LCA process involves four major steps: defining the goal and scope, developing a life-cycle inventory (LCI), performing a life-cycle impact assessment (LCIA), and interpreting the results (ISO 14044, 2006). LCA can be either evaluate the entire product life cycle, commonly known as "cradle-to-grave," or focus on specific stages such as "cradle-to-gate" or "gate-to-gate (Puettmann et al., 2021).

The environmental impacts of wood-based products vary due to differences in harvesting methods, transportation distances, and manufacturing technologies. Abbas & Handler (2018) conducted a LCA study on the harvesting and transportation of hardwood and softwood species in Tennessee, USA, focusing primarily on oak, hickory, and some pine species. Using the SimaPro LCA tool, they found that transportation distances significantly influence GHG emissions in wood supply chains, while harvesting methods, such as chainsaw-based versus feller buncher-based systems, yield varying energy demands and emissions (Abbas & Handler, 2018). Gu et al. (2022) conducted a cradle-to-gate LCA to evaluate the environmental impacts of transporting mass timber products for a mid-rise institutional building in New Brunswick, Canada. Their study compared a steel frame building with a mass timber alternative and found that the mass timber design resulted in higher impacts on smog formation, acidification, and eutrophication. These increased impacts were attributed to longer transportation distances and greater diesel fuel consumption required to transport mass timber components to New Brunswick (Gu et al., 2022). Moreover, regional energy sources also affected impacts; for instance, hydro-based energy in the Pacific Northwest results in lower GWP compared to coal-based energy in the Southeast USA (Milota & Puettmann, 2017). Meil et al. (2009) examined the status of energy use in Canadian wood products sector, and they discovered that the manufacturing process is the most energy-intensive processes, particularly kiln drying, which accounts for the majority of energy consumption in lumber production (Meil et al., 2009). Bergman & Bowe (2008) studied hardwood lumber manufacturing using life-cycle inventory (LCI) methodology and reported that hardwood lumber production required more thermal and electrical energy than softwood lumber due to its higher density and longer drying time

(Bergman & Bowe, 2008). Furthermore, Puettmann & Lippke (2012) used SimaPro LCA software to study the effects of substituting natural gas with wood pellets, mill waste, and forest waste for electricity generation or heat production during drying. They found that using woody biomass significantly reduces carbon emissions compared to fossil fuels (Puettmann & Lippke, 2012).

This case study was aimed at conducting a cradle-to-gate LCA of the production of hardwood lumber, in an effort to understand how well it aligns with New Brunswick's action plans set out in 2016. The analysis measured the environmental impacts from the extraction of raw materials, including harvesting in this case, and continuing through to the production of rough green hardwood lumber in New Brunswick, Canada, at the point of which the hardwood lumber was the raw material used to produce the products without experiencing kiln-drying, such as pallets and railway ties. Therefore, the findings of this study could provide a foundational base for conducting cradle-to-grave LCAs for secondary hardwood products.

4.2 Materials and Methods

4.2.1 Goal and scope of LCA

The objective of this study was to evaluate the cradle-to-gate environmental performance of the production of hardwood lumber and develop a LCI for producing hardwood lumber in New Brunswick, Canada. Additionally, the study was aimed at comparing the results with the cradle-to-gate LCA of the production of softwood lumber in the same region. The scope of this study is given as follows:

4.2.1.1 Functional Unit

To assess a product's total life cycle environmental impact, the functional (reference) unit of the product must be first defined to assemble the inputs and outputs for different environmental impacts. Given that the analysis focused on the primary hardwood lumber product, one m^3 of rough green hardwood lumber (1 m^3) was defined as the functional unit in this LCA study.

4.2.1.2 System Boundary

The system boundary of this study is Cradle-to-Gate, encompassing the extraction of resources (i.e. tree harvesting), transportation of harvested trees to the sawmill plants, and the production of hardwood lumber, focusing on debarking and sawing processes only (Figure 4-1). Drying and planing unit processes were excluded from this study because the focus was on the production of rough green hardwood lumber, which is primarily used to produce pallets and railway ties in the mill examined.

Forest management activities such as fertilization, thinning, planting seedlings, and nursery operations were not included. Only the final harvesting phase provided first-hand (data) information as resource extraction.

Major fuels like diesel, gasoline use, and the primary fuels to generate electricity were collected for modeling the LCA within the system boundary. Additionally, important ancillary materials such as hydraulic fluids, motor oils, greases, and plastic strapping were considered within the system boundary.

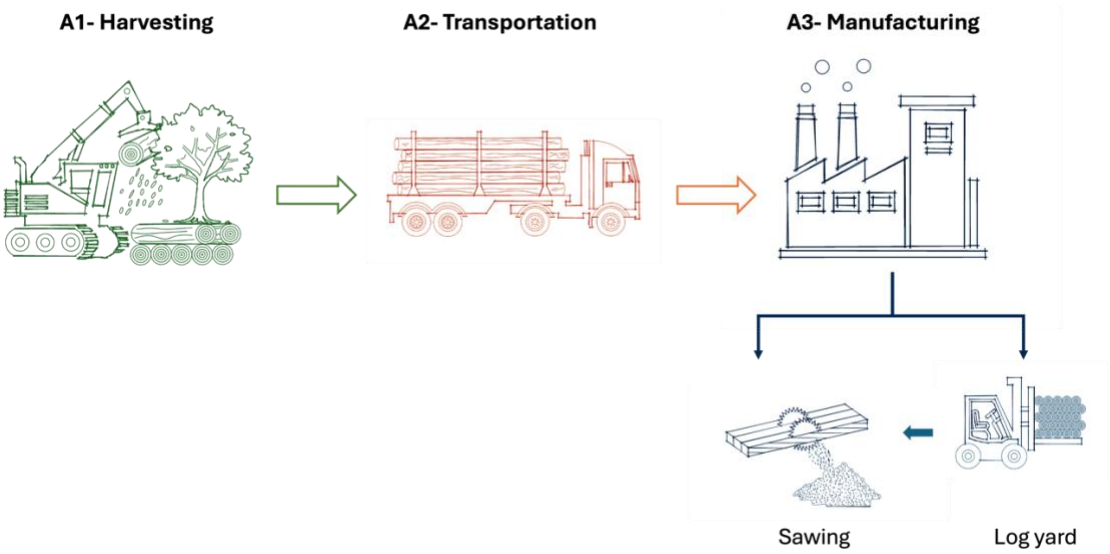


Figure 4-1: Diagram of the lumber manufacturing process for producing hardwood lumber in New Brunswick, Canada.

4.2.2 Life Cycle Inventory

In this study, data on material and energy inputs were collected via survey questionnaires for log harvesting and site visits for sawmill manufacturing. The samples included one logging company and two types of hardwood sawmills in a facility in New Brunswick: one mill focused on producing pulp chips in addition to rough green lumber from low-quality logs, and the other primarily producing lumber from high-quality logs. The year 2022 was chosen as the representative year for this analysis. Material and energy consumption values for hardwood lumber production were determined by surveying one hardwood logging company and two types of hardwood mills, including hardwood sawlogs (high grade) and hardwood pulpwood/pallet, in New Brunswick, Canada. Detailed questionnaires, follow-up emails, and site visits were conducted to gather the data. Data from the mill questionnaire were weighted-averaged using Equation (1):

$$\bar{P}_{Weighted} = \frac{\sum_{i=1}^{n} P_i x_i}{\sum_{i=1}^{n} x_i} \qquad (1)$$

Where, P is the weighted average of the values reported by the mills, Pi is the reported mill value, and xi is the fraction of the mill's value to total production for that specific value. An input/output process-based modeling approach for the LCI method was used, ensuring consistency and accuracy in the analysis.

Secondary data of life cycle emissions from use of diesel, gasoline, propane, grid energy mix, auxiliary materials, and transport were sourced from the DataSmart LCI database (LTS, 2023), which is specifically built for North American SimaPro users. The DataSmart LCI database provides comprehensive LCI data tailored to North America, incorporating U.S.-specific geographic and technological details. It is based on foundational datasets

from US LCI v.1.60 and Ecoinvent v.2.2. The US LCI database v.1.60 provides detailed inventory data for energy production, industrial processes, and transportation specific to the United States. Ecoinvent v.2.2 complements this by offering extensive global data for processes and materials not covered in US LCI. DataSmart builds on these datasets by incorporating additional regional data developed by Long Trail Sustainability (LTS), ensuring it is comprehensive and tailored to North American contexts.

4.2.2.1 Resource Extraction

Total production of harvested logs, including bark, in 2022 was 305,000 m^3 from the one harvesting company that participated in the survey. Overall, four hardwood species, yellow birch (*Betula alleghaniensis*), white birch (*Betula papyrifera*), sugar maple (*Acer saccharum*) and red maple (*Acer rubrum*), represented 70% of the species mix harvested. Twenty percent was aspen (*Populus tremuloides*) and a small amount of softwood is also harvested from mixed forest stands. As reported, hardwood trees on average returned 10% high-grade sawlogs, 30% pallet-grade logs, and 60% pulp-wood grade logs (Personal Communications, 2024). Fully mechanized systems were used for harvesting. Diesel and gasoline served as the process's primary energy inputs, with the utilization of ancillary materials such as motor oil, grease, hydraulic fluid, lubricating fluid, and antifreeze. The equipment used included feller buncher, forwarder, single grip processor, grapple skidder, delimber and slasher. Moreover, 18 trucks were used for to transport logs in the woods, 13 self-loader trucks and 5 quads with a loader. The main product of this process was logs destined for lumber mills. The co-product, non-merchantable slash, was generally recovered or left on the ground. However, the survey respondents assumed in this study

the residues left to decay during harvesting to be about 0.165 m^3 per m^3 of roundwood. The energy and ancillary material inputs used per m^3 of roundwood by the logging company that participated in the survey is shown in Table 4-1.

Table 4-1: Inventory data of Resource Extraction.

Resource	Inputs	Unit	Amount per m^3 of roundwood
Energy	Diesel fuel	litre	3.69
	Gasoline	litre	0.70
	Propane	litre	0.01
Ancillary Materials	Hydraulic fluid	litre	0.054
	Motor oil	litre	0.02
	Greases	kg	0.0017
	Antifreeze	litre	0.0014

4.2.2.2 Transport of Raw Materials from the Extraction Site to the Sawmill

Logs were transported by diesel trucks to the mills, with an average one-way distance of 118 km. This transportation was modeled as a stand-alone unit process rather than an input to the log yard process (Table 4-2). The calculation of 104 tkm (tonne-kilometers) was based on the average green mass of 1 m^3 logs, calculated as 883 kg, and the transportation distance in kilometers.

Table 4-2: Inventory for Transportation to the Sawmills.

		Amount	Unit	Allocation (%)
Output	Log at mill (including bark)	1	m^3	100
Input	Log at forest road (including bark)	1	m^3	-
	Transport, combination truck	104	tkm	-

4.2.2.3 Product Manufacturing process

This study considered lumber manufacturing processes, specifically focusing on log yard and sawing operations, with an emphasis on producing 'green' lumber. In 2022, the surveyed sample mills produced approximately 56,864 thousand board feet (MFBM) (161,493 m^3) of rough green lumber. Annual lumber product output (rough green) was reported by the mill in MFBM. A conversion factor from MFBM to m^3 for rough green lumber was assumed to be 2.36 m^3/MFBM. It was assumed that 100% of the production was sold either as lumber to an external client or transferred (sold) to another mill for further transformation.

4.2.2.4 Species, Moisture Content, and Specific Gravity of the Woods Examined

Birches, aspens, and maples were included among the types of wood species used to produce hardwood lumber in both mills, as reported by the sawmill manufacturing. Samples from different parts of the tree logs, including full-length logs and tree-top logs, were taken from the hardwood sawmills to determine the moisture content (MC) and specific gravity (SG) of the lumber. A full-length log refers to the main trunk section(s) of a tree, which is longer and typically of higher quality, used predominantly for lumber products. A tree-top log, on the other hand, is the smaller section(s) near the crown of the tree and are generally of lower quality, often utilized for by-products such as chips, pulpwood, or biomass energy. The samples were then sent to the University of New Brunswick's Wood Science and Technology Center (WSTC) in Fredericton, Canada, for measuring the volume and weight of the samples and physical properties such as MC and SG following ASTM D143 standard (ASTM International, 2023). These two attributes

were crucial for data calculation and conversion in the following LCA analysis, ensuring an accurate mass balance.

Table 4-3 shows that the average MC was 67%, and the average green SG was 0.532 for the lumber examined. These values were calculated based on the weighted average of species distribution percentages, MC, and SG for each species. Data on both green and oven-dry weights were used to calculate MC, while green volume and oven-dry weight were used to calculate SG for samples from each mill.

Table 4-3: Average physical properties of the log species sawn into lumber.

Species	Contribution (%)	MC (%)	Green SG[1]
Birch (*Betula spp.*)	50	65	0.530
Maple (*Acer spp.*)	32	58	0.594
Aspen (*Populus spp.*)	17	89	0.421
Weighted average		67	0.532

[1] The ratio of a wood's oven-dry weight to the weight of an equal volume of water, using its fully saturated volume.

In order to calculate the oven-dry (OD) weight of the chips, sawdust and bark, the weighted average MC of these by-products was determined using the sample measurement method. Samples were cut to include both heartwood and sapwood. The sapwood MC was assumed to be the same as the MC of the bark and sawdust, while the MC of chips was considered a mix of sapwood and heartwood MC (Athena Sustainable Materials Institute, 2018). Consequently, the reported co-products included green chips with a MC of 67%, and sawdust and bark with a MC of 71%.

4.2.2.5 Lumber Manufacturing Mass Balance and Conversion Efficiencies

Mass balance involves accounting of all material inputs and outputs within a defined system boundary, including all the processes. In this study, mass balance was performed based on the oven dry mass of roundwood inputs and process outputs (i.e., rough green lumber and co- products), using the properties found in sample measurements and provided by the surveyed sawmills. 1461 oven dry (OD) kg of incoming hardwood logs including bark with a density of 883 kg/m^3 produced 1.0 m^3 (532 OD kg) rough green lumber, for roughly 64% reduction in mass. For the co-products, the OD weight of the total value reported by mills was calculated per m^3 of rough green hardwood lumber. Table 4-4 provides a mass balance for New Brunswick hardwood lumber manufacturing.

Table 4-4: Wood mass balance for 1 m^3 of rough green lumber (values in oven dry kg).

Material type	Sawing process	
	Input (kg)	Output (kg)
Logs	1336.4	
Green chips		692.5
Sawdust		111.9
Bark	124.7	124.7
Rough green lumber		532
Total OD Mass	1461.1	1461.1

Cubic Lumber Recovery (CLR) was calculated by determining the m^3 of lumber produced per m^3 of log input. In this study, the breakdown of logs into rough green lumber during sawing resulted in a weighted average CLR of 0.36 m^3 of rough green lumber per m^3 of logs. This means that, on average, 2.75 m^3 of logs are sawn to produce 1.0 m^3 of rough green lumber. Therefore, the total volume conversion from incoming logs to lumber product is 36.4%.

4.2.2.6 Gate-to-Gate Energy and Material Input/Output

Lumber manufacturing process to produce the rough green lumber was divided into two unit processes, log yard and sawing. The weighted average material flows, energy use in the lumber manufacturing process were normalized to 1.0 m^3 volume of each unit process: i.e. per m^3 of log in the log yard and per m^3 of rough-green lumber in the sawmill.

4.2.2.7 Log yard

The log yard process included unloading log trucks, scaling logs (reporting logs for volume in m^3), sorting logs on decks, and moving logs to the sawmill. Diesel was the most often used fuel for equipment, such as loaders, forklifts, and other on-site transportation to move logs around the log yard, with gasoline being used to a lesser extent. There was also grease, antifreeze, hydraulic oil, and lubricant utilized. In the log yard, a small quantity of electricity was used. Outputs include logs with bark at the log yard (Table 4-5).

Table 4-5: Unit process inputs/outputs for log yard activities to produce 1 m^3 of green logs.

		Amount	Unit	Allocation (%)
Output	Log at log yard (Including Bark)	1	m^3	100
Input	Log at mill (Including Bark)	1	m^3	
	Gasoline	0.02	l	
	Diesel	3.03	l	
	Hydraulic fluid	0.04	l	
	Motor oils	0.0074	l	
	Grease	0.00077	kg	
	Antifreeze	0.00094	l	
	Electricity	0.143	kWh	

4.2.2.8 Sawing (Production of Rough Green Lumber)

The sawing unit process involved several stages, including debarking logs, transforming logs into rough-green lumber, sorting rough-green lumber by size, and stacking the lumber for drying. Key inputs included logs with bark, diesel and gasoline as fuels, and ancillary materials such as lubricant oil, hydraulic oil, grease, and antifreeze. Electricity was the primary energy input in the sawing process. The mills also burned their own wood wastes in an industrial boiler for heating the facility. However, the data of their consumption was not reported. The process generated outputs including green lumber at 36%, green chips at 47%, green sawdust at 8%, and bark at 9%. Allocation of products and coproducts was based on oven-dry mass. Chips were either sold to external clients (Paper Mills) or used by the Pellet plant. Sawdust was similarly used in the Pellet plant for making pellets. Bark was either sold or used in the boilers for heating and drying purposes.

Table 4-6 summarizes the products and co-products outputs, as well as inputs required for the sawing process, which yields 1 m^3 of rough sawn green lumber in the New Brunswick hardwood sawmills.

Table 4-6: Unit process inputs/outputs for sawing to produce 1 m^3 of rough green hardwood lumber.

		Amount	Unit	Allocation (%)
Output	Rough green lumber	1	m^3	36
	Green Chips	692.50	kg	47
	Sawdust	111.9	kg	8
	Bark	124.67	kg	9
Input	Roundwood	2.75	m^3	
	Gasoline	0.00513	l	
	Diesel	0.814	l	
	Hydraulic fluid	0.0373	l	
	Grease	0.00372	kg	
	Electricity	61.44	kWh	
	Lubricant fluid	0.437	l	
	Plastic strapping	0.116	kg	

4.2.2.9 Secondary Data Sources

Table 4-7 lists the secondary LCI data sources used in this LCA study for raw material inputs, ancillary materials and packaging, transportation, fuels and energy for manufacturing. The assumptions are based on the DataSmart LCI database, utilizing U.S. Life Cycle Inventory (US LCI v1.60) and Ecoinvent v2.2 datasets. These datasets are adapted to reflect the North American context, including the electricity mix specific to New Brunswick.

Table 4-7: Material LCI data drawn from the DataSmart database (LTS, 2023). All data are for North America, except electricity (Canada), and reflect the year 2018.

Data	LCI Data Source
Diesel	US EI 2.2 (DataSmart2023): Diesel, combusted in Industrial equipment NREL/US U
Gasoline	US EI 2.2 (DataSmart2023): gasoline, combusted in industrial equipment/US
Propane	US EI 2.2 (DataSmart2023): Liquefied petroleum gas, combusted in industrial boiler/US
Electricity	Electricity mix, New Brunswick/CA U
Hydraulic fluid, Lubricant oil	US EI 2.2 (DataSmart2023): Lubricating oil, at plant/US- US-EI U
Motor oil, Greases	US EI 2.2 (DataSmart2023): Diesel, at refinery/l NREL /US
Antifreeze	US EI 2.2 (DataSmart2023): ethylene glycol, at plant/US - US-EI U
Plastic strap	US EI 2.2 (DataSmart2023): Polyethylene, HDPE, granulate, at plant/ US- US-EI U
Trucking	US EI 2.2 (DataSmart2023): Transport, combination truck, Diesel powered NREL/US U

4.3 Life Cycle Impact Assessment (LCIA)

Linking the LCI to potential impacts on the environment is the goal of the LCIA phase. SimaPro v9.6.0.1 (PRé Sustainability B.V. 2024) was used to generate LCIA results of this cradle-to-gate hardwood lumber product system. All inputs and outputs for each unit process were carefully modeled within SimaPro to ensure accurate representation of the processes involved. The midpoint impact categories for acidification, eutrophication, global warming, smog, and ozone depletion were determined using the TRACI method (Bare et al., 2011), due to its characterization factors, which specifically designed to quantify environmental impacts in alignment with U.S. These factors ensure consistent, accurate assessments, producing results that are both scientifically valid and regionally relevant. While the TRACI method considers fossil fuel depletion, it does not include primary energy use as an impact category. Consequently, the Cumulative Energy Demand (CED) method (Frischknecht et al., 2007) was also utilized. CED calculates the total energy derived from all sources directly extracted from the earth, including natural gas, oil, coal, biomass, nuclear, and hydropower. This total primary energy is further categorized into non-renewable fossil, nuclear, and renewable energies.

Cradle-to-gate environmental performance outputs for the reported indicators are listed in Table 4-8 for one m^3 of hardwood rough green lumber produced in the New Brunswick region. It separates the impact values from A1 stage (resource extraction), A2 stage (transportation), and A3 stage (hardwood rough green lumber production). About 42% of the CO_2 eq or the Global Warming Potential (GWP) came from producing lumber (17 kg CO_2 eq). Thirty four percent is from harvesting operations with 13.8 kg CO_2 eq. Transportation, which is primarily the transport of logs to the sawmill, was 9.8 kg CO_2 eq

or 24% of the cradle-to-gate GWP impact. The total cradle-to-gate GWP impact to produce one cubic meter ($1m^3$) of rough green hardwood lumber is 40.7 kg CO_2 eq.

Table 4-8 also provides the values for the energy resources. The total energy consumption was 736 MJ/m^3, with 54% of that being for the manufacturing stage. Followed by that was harvesting and transportation with 28 and 18%, respectively. In this study, 98% of the total energy consumption was non-renewable, mainly from fossil sources used for machinery and transportation, amounting to 583.6 MJ/m^3. Due to the exclusion of drying processes and also the lack of on-site electricity generation, which typically involve biomass energy combustion, the total renewable energy consumption was significantly low, at just 11 MJ/m^3, making up only 2% of the total energy consumption (Figure 4-2). Moreover, electricity in New Brunswick does not mainly rely on renewable sources, with about 30% coming from fossil sources such as hard coal and natural gas. Harvesting, on the other hand, was a fossil energy-intensive process that relied on diesel use for heavy machinery and gasoline for crew transport.

Table 4-8: Cradle-to-gate environmental performance of 1 m^3 rough green hardwood lumber based on mass allocation for New Brunswick, Canada.

	Environmental Indicator	Unit	Total	A1	A2	A3
Impact Category	Global Warming	kg CO_2 eq	40.67	13.82	9.84	17.01
	Acidification	kg SO_2 eq	0.40	0.18	0.054	0.17
	Eutrophication	kg N eq	0.045	0.014	0.005	0.026
	Smog	kg O_3 eq	12.07	5.74	1.57	4.76
	Ozone Depletion	kg CFC-11 eq	9.88E-07	6.42E-08	1.64E-08	9.08E-07
	Fossil Fuel Depletion	MJ surplus	73.71	27.28	17.43	29.00
Energy Consumption	Total primary energy	MJ	736.08	207.75	132.69	395.64
	Non-renewable fossil	MJ	583.66	204.74	130.79	248.13
	Non-renewable nuclear	MJ	141.32	2.82	1.78	136.71
	Renewable biomass	MJ	5.09	0.074	0.045	4.98
	Renewables (solar, wind, hydro, geothermal, and biomass)	MJ	6.00	0.11	0.063	5.83

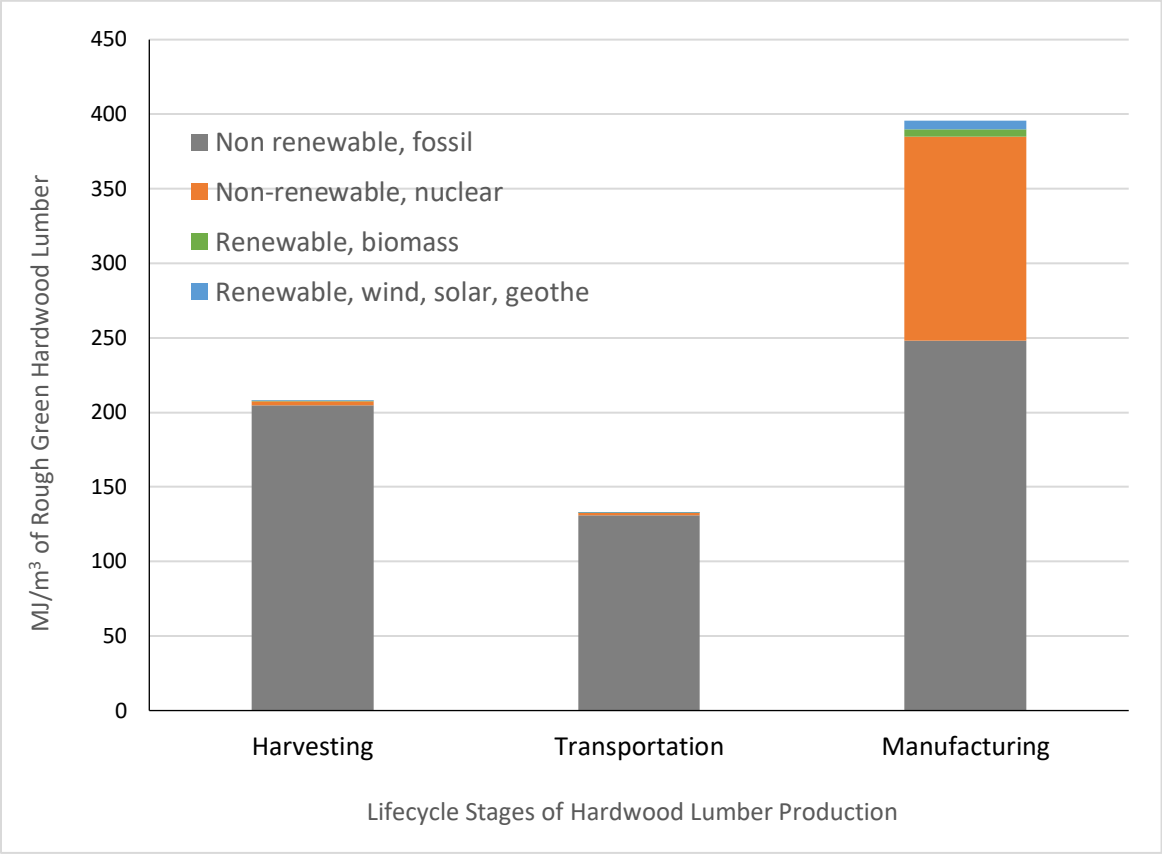


Figure 4-2: Energy consumption across different stages of producing 1 m^3 of rough green hardwood lumber in New Brunswick, Canada.

Figure 4-3 shows the contributions of the resource extraction, transportation, and manufacturing stage (A3) in the six midpoint environmental impacts for the cradle-to-gate LCA of hardwood lumber production. Compared with all stages, lumber production (A3) represented the highest impacts for ozone depletion, global warming, eutrophication, and fossil fuel depletion environmental impact categories with 92, 42, 58 and 39%, respectively. However, resource extraction (A1) had the largest effects on the smog and acidification impact category, differing from lumber production (A3) by a very little margin.

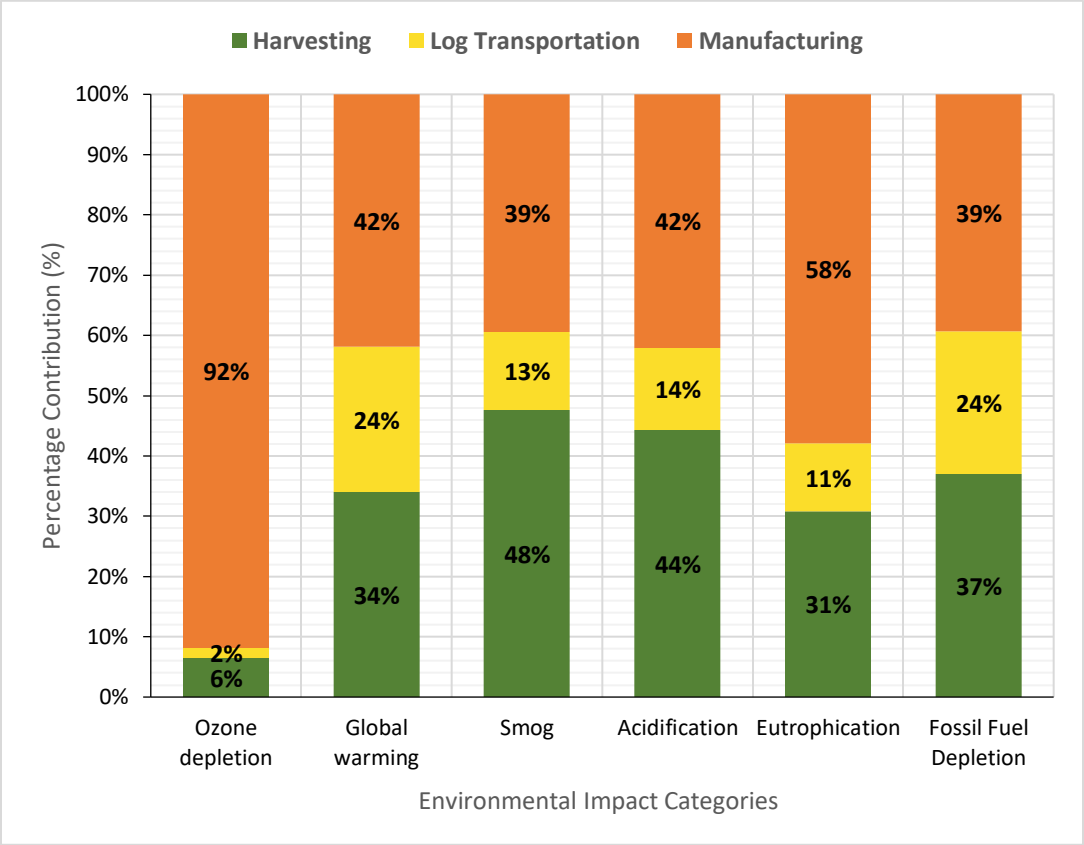


Figure 4-3: Contribution of stages in environmental impacts for the cradle-to-gate life-cycle stages of 1 m^3 rough green hardwood lumber produced in New Brunswick, Canada.

4.4 Biogenic Carbon

Hardwood lumber in service stores carbon. The production of 1 m^3 of rough green hardwood lumber in New Brunswick emitted 41 kg CO_2 eq. However, the carbon stored in the same 1 m^3 of lumber was assumed to be 50% by mass of OD wood (Bergman et al., 2014). Therefore, the carbon stored in 1 m^3 (532 OD kg) of rough green hardwood lumber amounts to 266 kg of carbon. Multiplying the 44/12, which accounts for the conversion of carbon (atomic weight of 12) to carbon dioxide (molecular weight of 44), this equates to 975 kg of CO_2 stored, which is approximately 24 times greater than the carbon emitted during the cradle-to-gate LCA study.

$$\text{Carbon stored} = 0.50 \times 532\text{kg} = 266 \text{ kg C}$$

$$CO_2 \text{ stored} = 266\text{kg} \times 44/12 = 975\text{kg } CO_2 \text{ eq}$$

4.5 Variation and Sensitivity Analysis

Sensitivity analysis was used with the aim to assess the reliability of the model outputs by evaluating the effects in model predicted results when making changes in input parameters. In this study, due to variations among different data of two hardwood sawmills, some uncertainty existed in the results. Table 4-9 shows various statistics for the most significant modeling parameters in hardwood lumber production, such as CLR and electricity used in sawing. These two variables were selected because of the significant differences observed between the two surveyed sawmills. The standard deviation for each parameter, calculated from the sample data, was used to conduct a sensitivity analysis.

Table 4-9: Data statistics analysis for selected parameters.

Inventory Parameter	Units	Weighted Average	Std. deviation	Min	Max	Mean
Electricity (A3 input)	kWh	61.44	33.03	39.61	86.32	62.96
CLR (A3 input)	m^3 rough green lumber /m^3 log	0.36	0.21	0.26	0.56	0.41

With this purpose, significant inventory parameters were altered to investigate their effect on the LCIA results. The proportion of their alternation was calculated based on the standard deviation and baseline value of each parameter. For instance, the baseline value for CLR was 0.36, with a standard deviation of 0.21, representing 58% of the baseline value. As lumber recovery increased, a larger share of the impact was allocated to the main product. Table 4-10 shows that altering the CLR baseline by 58% and the electricity baseline by 54% resulted in an 11% and approximately 8% increase in total GWP, respectively. Additionally, both parameters significantly affected indicators, including ozone depletion potential and primary energy use (non-renewable nuclear and renewable energy).

Table 4-10: Sensitivity analysis.

Impact Category	Unit	Baseline results	Electricity (%)		CLR (%)	
			-54	+54	-58	+58
Global warming potential	kg CO_2 eq	40.67	-9	8	-11	11
Acidification	kg SO_2 eq	0.40	-4	4	-7	7
Eutrophication potential	kg N eq	0.045	-18	18	-21	21
Smog potential	kg O_3 eq	12.07	-1	1	-4	4
Ozone depletion potential	kg CFC11e	9.88E-07	-40	40	-49	49
Total primary energy	MJ	736.08	-17	16	-19	19
Non-renewable fossil	MJ	583.66	-8	7	-11	11
Non-renewable nuclear	MJ	141.32	-51	51	-52	52
Renewable biomass	MJ	5.09	-19	19	-53	53
Renewables (solar, wind, hydro, geothermal, and biomass)	MJ	6.00	-51	51	-53	53

4.6 Discussion

Hardwood lumber production processes included in the manufacturing stage are log-yard operations and primary log breakdown (sawing). To compare this with a cradle-to-gate LCA study of softwood lumber produced in New Brunswick, Canada, the same system boundary up to the sawing stage was considered. Therefore, the drying and planing unit processes in the softwood LCA study were not included to ensure comparability.

The LCI for softwood lumber production showed less electrical consumption in the sawing unit process, at 47 kWh per m^3 of rough green lumber, compared to hardwood, which was 61 kWh per m^3. This difference could be attributed to the fact that hardwoods are generally denser than softwoods, and since hardwood lumber is typically sawn to thinner dimensions, more electrical energy is consumed in the sawing process (Bergman & Bowe, 2008). Table 4-11 summarized the differences in data between softwood and hardwood sawmills, focusing on resource extraction, transportation and sawing stages, including inputs and outputs. However, as mentioned in detail in section 5, the value represented the weighted average of two types of hardwood sawmills (sawlogs or high grade and hardwood pulpwood/pallet), which might have caused significant differences between the LCI values for each hardwood mill. This was evidenced by the finding that the electricity consumption for hardwood logs converted to high-grade lumber was almost half that of pallet lumber production. Additionally, the CLR was twice as high in high-grade sawlog production compared to the pallet lumber plant.

Table 4-11: Differences in data between softwood and hardwood sawmills, focusing on resource extraction, transportation and sawing stages.

	Per m^3 of lumber	**Softwood**	**Hardwood**
Resource Extraction Stage	**Ancillary materials** **(**Hydraulic fluid, motor oil, Grease)	Almost the same	Almost the same
	Energy		
	Diesel fuel (l)	2.94	3.69
	Gasoline (l)	0.14	0.70
	Propane (l)	0.02	0.01
Transportation		67 tkm	104 tkm
Log yard and Sawing Stage	**Sawing yield (log/m^3 lumber)**	2.21	2.75
	Energy		
	Gasoline (l)	0.013	0.025
	Diesel (l)	1.72	3.84
	Electricity (kWh)	47.25	61.58
	Ancillary materials		
	Hydraulic fluid, Lubricant oil (l)	0.23	0.51
	Grease (kg)	0.0014	0.0045
	Motor Oil (l)	0.0063	0.0074
	Antifreeze (l)	0.00033	0.00094

Table 4-12 compares the results of the previous study (rough green softwood lumber) and this study (rough green hardwood lumber). The total GWP in the current study was 54% higher than that reported for softwood production. This increase was primarily attributed to a 69% higher GWP impact during the manufacturing stage, which encompassed the activities such as log yard operations and sawing processes. The higher GWP impact was driven by lower hardwood lumber yields, which necessitate processing more logs to produce the same volume of lumber, combined with increased diesel and electricity consumption during production. As re-ported by Bergman & Bowe (2008), hardwood lumber production required more electrical energy because of their higher density and smaller dimensions relative to softwoods. These factors collectively contributed to the higher energy inputs and associated GWP impacts in hardwood lumber production (Bergman & Bowe, 2008). These impacts could be mitigated by adopting on-site energy generation for electricity, particularly through the use of biomass from sawmill by-products, which can reduce reliance on off-site energy sources. Other significant differences in the impacts included smog, acidification, and eutrophication, with increases of 68, 63, and 40%, respectively. While the higher diesel consumption in manufacturing and harvesting for hardwood lumber production significantly influenced these impact categories, the higher green density of hardwood lumber and the longer transportation distance found in this study compared to the softwood one, and its associated impacts, were probably the primary causes of the increased eutrophication, acidification, and smog effects. agreed with the findings by Gu et al. (2022), which was aimed at understanding the environmental impacts of transporting mass timber products (MTPs) for a mid-rise institutional building in New Brunswick, Canada. The research compared the

environmental performance of a steel frame building with an alternative mass timber design using a cradle-to-gate LCA. Using SimaPro software and the TRACI impact assessment method, that study found that the mass timber had lower global warming and ozone depletion impacts compared to a steel frame design. However, it also showed higher impacts in smog formation, acidification, and eutrophication due to the longer transportation distance of mass timber components to New Brunswick and the increased diesel fuel consumption during transportation (Gu et al., 2022).

Moreover, there was a 41% increase in total primary energy use in the production of hardwood lumber in this study (736 MJ/m^3) compared with the softwood study (520 MJ/m^3), which was mainly due to the higher use of non-renewable fossil energy with an almost 55% increase in the current study. However, the non-renewable nuclear, renewable biomass, and other renewable sources of energy consumption did not change significantly as the sources of raw materials were the same and both studies were done in New Brunswick considering the same regional source of energy. Kelley et al. (2020) pointed out that it was essential to reduce fossil fuel dependence in lumber production, transitioning to renewable energy for on-site electricity generation (Kelley et al., 2020). Sawmills could utilize biomass energy from by-products such as sawdust and bark for co-generation, reducing reliance on grid electricity in New Brunswick, which derived about 30% of its energy from fossil sources such as hard coal and natural gas, and nearly 40% from nuclear power (LTS, 2023). Additionally, improving lumber yield through advanced sawing technologies and better material handling practices could significantly enhance efficiency and reduce waste.

Due to the exclusion of processes in this study, such as drying and planing, as well as other stages such as use and end-of-life stages, the findings from this study failed to fully assess the environmental impact across the entire lifecycle of the production of hardwood lumber. Extending the analysis to a cradle-to-grave framework in future studies would provide a more comprehensive understanding of the production of hardwood lumber in New Brunswick, Canada. Furthermore, this study's reliance on data from a small number of hardwood sawmills, due to incomplete data and limited willingness of sawmills to share operational information, restricts the representativeness of the results. Expanding the dataset to include a larger number of sawmills is essential to obtain more diverse and comprehensive data, ultimately improving the accuracy and reliability of the LCA analysis on the production of hardwood lumber in the province.

Table 4-12: LCIA comparison between cradle-to-gate LCA of softwood lumber production (up to the sawing stage) and that of hardwood lumber production (this study) in New Brunswick, Canada.

Impact Category	Unit	Rough green Hardwood Lumber, NB	Rough green Softwood Lumber, NB	Percent change (%)
Global warming potential	kg CO_2 eq	40.67	26.48	54
Acidification	kg SO_2 eq	0.40	0.24	63
Eutrophication potential	kg N eq	0.04	0.03	40
Smog potential	kg O_3 eq	12.07	7.16	68
Ozone depletion potential	kg CFC11eq	9.88E-07	8.99E-07	10
Total primary energy	MJ	736.07	520.38	41
Non-renewable fossil	MJ	583.66	376.17	55
Non-renewable nuclear	MJ	141.31	133.67	6
Renewable biomass	MJ	5.09	4.75	5
Renewables (solar, wind, hydro, geothermal, and biomass)	MJ	6.00	5.70	5

4.7 Conclusions

A cradle-to-gate LCA of the production of rough green hardwood lumber in New Brunswick, Canada, was conducted, integrating impact assessments and LCI data on forest resource extraction, transportation, and manufacturing processes, using both primary and secondary data sources. The following conclusions could be drawn:

- The manufacturing stage accounted for 54% of total primary energy consumption and had the highest GWP impact at 42%, with most electricity at mill sites sourced off-site, relying 98% on non-renewable energy and only 2% on renewable sources.
- Harvesting and transportation contributed approximately 28 and 18%, respectively, to the overall energy consumption.
- The higher manufacturing energy consumption and GWP in hardwood production compared to softwood were primarily attributed to the greater electrical energy required for sawing hardwood and its lower lumber yield.
- Rough green hardwood lumber stored 24 times more carbon than its cradle-to-gate CO_2 eq emissions released.

It is recommended that on-site energy generation using wood residues has the potential to reduce dependence on non-renewable fossil fuels while significantly lowering emissions, particularly in electricity generation processes. Moreover, improving lumber yield rate through adopting advanced sawing technologies, such as artificial intelligence, would enhance the efficiency of lumber production and reduce the GWP impact. Future research should incorporate cradle-to-grave LCAs and foster collaboration with more sawmills to provide more reliable data representativeness.

References

Abbas, D., & Handler, R. M. (2018). Life-cycle assessment of forest harvesting and transportation operations in Tennessee. Journal of Cleaner Production, 176, 512–520. https://doi.org/10.1016/j.jclepro.2017.12.080

ASTM International (2023) Standard test methods for small clear specimens of timber (ASTM D143-14). West Conshohocken, PA: ASTM International. https://doi.org/10.1520/D0143-14

Athena Sustainable Materials Institute. (2018). A Cradle-to-Gate Life Cycle Assessment of Eastern Canadian Surfaced Dry Softwood Lumber. https://www.athenasmi.org/wp-content/uploads/2018/07/CtG-LCA-of-Eastern-Canadian-Surfaced-Dry-Softwood-Lumber.pdf.

Bare, J. C. (2011). TRACI 2.0: The tool for the reduction and assessment of chemical and other environmental impacts 2.0. Clean Technologies and Environmental Policy, 21 January 2011.

Bergman, R. D., & Bowe, S. A. (2008). Environmental impact of producing hardwood lumber using life-cycle inventory. Wood and Fiber Science, 40(3), 448-458.

Bergman, R., Puettmann, M., Taylor, A., & Skog, K. E. (2014). The carbon impacts of wood products. Forest Products Journal, 64(7/8), 220–231. https://doi.org/10.13073/FPJ-D-14-00047

Frischknecht, R.; Jungbluth, N.; Althaus, H.J.; Doka, G.; Dones, R.; Hischier, R.; Hellweg, S.; Humbert, S.; Margni, M.; Nemecek, T.; Spielmann, M. (2007). Implementation of

Life Cycle Impact Assessment Methods: Data v2.0. ecoinvent report No. 3, Swiss centre for Life Cycle Inventories, Dübendorf, Switzerland.

Gong, M. (Ed.). (2022). Engineered wood products for construction. IntechOpen. https://doi.org/10.5772/intechopen.92960

Government of New Brunswick. (2018). Climate Change Act. Retrieved July 17, 2024, from https://laws.gnb.ca/en/pdf/as/2018,%20C.11.pdf

Government of New Brunswick. (2016). Transitioning to a low-carbon economy: New Brunswick's climate change action plan. Government of New Brunswick. Retrieved July 17, 2024, from https://www2.gnb.ca/content/dam/gnb/Departments/env/pdf/Climate-Climatiques/TransitioningToALowCarbonEconomy.pdf

Grossi, F.; Ge, H.; Zmeureanu, R. Life Cycle Assessment of the Environmental Benefits of Using Wood Products and Planting Trees at an All-Electric University Laboratory. Buildings 2023, 13, 1584. https://doi.org/10.3390/buildings13071584

Gu, C., Gu, H., Gong, M., & Blackadar, J. (2022). A case study on the impact of transportation of mass timber products on the cradle-to-gate LCA results for an institutional building. Recent Progress in Materials, 4(3), 1. https://doi.org/10.21926/rpm.2203014

Gu, H., Nepal, P., Arvanitis, M., & Alderman, D. (2022). Carbon Impacts of Engineered Wood Products in Construction. IntechOpen. doi: 10.5772/intechopen.99193

Hemmati, M., Messadi, T., Gu, H., Seddelmeyer, J., & Hemmati, M. (2024). Comparison of embodied carbon footprint of a mass timber building structure with a steel equivalent. Buildings, 14(5), 1276. https://doi.org/10.3390/buildings14051276

Hubbard, S., Bergman, R., & Sahoo, K. (2020). A life cycle assessment of hardwood lumber production in the Northeast and Northcentral United States. https://doi.org/10.13140/RG.2.2.20583.06561.

ISO 14040. (2006a). Environmental management – Life cycle assessment – Principles and framework. International Organization for Standardization, Geneva, Switzerland.

ISO 14044 (2006b) Environmental management - life-cycle assessment - requirements and guidelines. International Organization for Standardization, Geneva, Switzerland.

Kelley, S.; Gustafson, R.; Puettmann, M.; Oneil, E.; Lippke, B.; Morales-Vera, R.; Mason, L. Carbon Cycling, Environmental and Rural Economic Impacts of Collecting and Processing Specific Woody Feedstocks in Biofuels; Consortium for Research on Renewable Industrial Materials (CORRIM): Corvallis, OR, USA, 2020; DOE-CORRIM-0002992-1.

Kutnar, A., & Hill, C. (2017). Life cycle assessment–opportunities for forest products sector. BioProducts Business, pp.52-64.

Intergovernmental Panel on Climate Change (IPCC). AR5 Synthesis Report: Climate Change 2014; IPCC: Geneva, Switzerland, 2014. Available online: https://www.ipcc.ch/site/assets/uploads/2018/02/SYR_AR5_FINAL_full.pdf (accessed on 29 December 2024).

LTS. (2023). DataSmart Life Cycle Inventory. Retrieved from https://longtrailsustainability.com/software/datasmart-life-cycle-inventory/ Accessed on 2023

Meil, J.; Bushi, L.; Garrahan, P.; Aston, R.; Gingras, A.; Elustondo, D. Status of Energy Use in Canadian Wood Products Sector; In Collaboration with FP Innovations-Forintek Division, Western Region; Natural Resources Canada: Ottawa, Canada, 2009.

Milota, M.; Puettmann, M.E. Life-Cycle Assessment for the Cradle-to-Gate Production of Softwood Lumber in the Pacific Northwest and Southeast Regions. For. Prod. J. 2017, 67, 331–342.

PRé Sustainability B.V. (2024). SimaPro (Version 9.6). Retrieved from https://simapro.com

Puettmann, M. E., & Lippke, B. (2012). Woody biomass substitution for thermal energy at softwood lumber mills in the US Inland Northwest. Forest Products Journal, 62(4), 273–279.

Puettmann, M., Bergman, R., Hubbard, S., Johnson, L., Lippke, B., Oneil, E., & Wagner, F. (2010). Cradle-to-gate life-cycle inventory of US wood products production: CORRIM Phase I and Phase II products. Wood and Fiber Science, 42(1), 15–28.

Puettmann, M., Pierobon, F., Ganguly, I., Gu, H., Chen, C., Liang, S., Jones, S., Maples, I., & Wishnie, M. (2021). Comparative LCAs of conventional and mass timber buildings in regions with potential for mass timber penetration. Sustainability, 13(24), 13987. https://doi.org/10.3390/su132413987

United Nations. (2023). Take urgent action to combat climate change and its impacts. Retrieved April 9, 2024, from https://sdgs.un.org/goals/goal13#progress_and_info

Ye, J., Fanyang, Y., Wang, J., Meng, S., & Tang, D. (2024). A literature review of green building policies: Perspectives from bibliometric analysis. Buildings, 14, 2607. https://doi.org/10.3390/buildings14092607

5 Comparative Whole Building Life Cycle Assessment on the Four Framing Systems of the Bakers Place using Tally LCA Tool

Abstract

The urgent need for climate change mitigation has increased the focus on reducing embodied carbon and energy, particularly in the construction sector. Utilizing sustainably sourced mass timber products provides a low-carbon alternative to traditional concrete and steel structural systems in buildings. These carbon impacts can be quantified by Whole Building Life Cycle Assessments (WBLCA), a systematic tool that evaluates the total environmental impact of a building, from material extraction and product manufacturing to construction, operation, and demolition. This study aimed to evaluate potential environmental impacts, especially the global warming potentials (measured as the greenhouse gas emissions or CO_2 eq), using a cradle-to-grave life cycle assessment (LCA) of a the 14-storey mass timber-steel hybrid building, named Bakers Place built in Madison, WI, USA. the Tally® LCA tool built in Autodesk® Revit® was used in the study. The baseline building was compared to functionally equivalent designs of full mass timber, full steel, and post-tensioned concrete as alternative structural framing materials. The results indicated that the full mass timber design had the lowest global warming potential (GWP), with the most significant difference being a 16% reduction as compared to the concrete design. The baseline hybrid design showed 14% lower GWP impact compared to the concrete alternative but slightly (1%) higher than the steel structure. Both hybrid and full mass timber designs demonstrated the biogenic carbon storage of approximately 1,910,490.5 kg and 2,497,649.5 kg CO_2, respectively. Additionally, the full mass timber

and the baseline hybrid designs showed a reduction in the use of non-renewable energy sources by about 30% compared to concrete and steel designs. While these findings highlighted the benefits of mass timber use in addressing climate change through reduced GHG emissions and lower non-renewable energy use, it is important to note that the hybrid and full-mass timber designs had higher impacts in other areas, such as acidification, eutrophication, ozone depletion, and smog formation.

Keywords: whole building Life cycle assessment; comparative LCA; mass timber; High-rise building; Greenhouse gas emissions; Global Warming Potential.

5.1 Introduction

The Intergovernmental Panel on Climate Change (IPCC) identified human-driven greenhouse gas (GHG) emissions as the likely dominant cause of global warming observed since the mid-20th century (IPCC, 2021). The building industry plays a significant role in contributing to these GHG emissions, as well as in the consumption of natural resources throughout its lifecycle—from construction to demolition. Buildings require energy at all stages, with direct energy used to maintain indoor environments, including heating, cooling, lighting, and appliance operation, referred to as operational carbon, and indirect needs, including the energy necessary for the production and installation of building materials, referred to as embodied carbon (Sartori & Hestnes, 2007). According to Architecture 2030, buildings are responsible for 42% of global CO_2 emissions, with 15%

attributed to structural materials and 27% to building operations (Architecture 2030, n.d.). As global construction activities continue to rise, many countries are increasingly committed to achieving the United Nations' Sustainable Development Goals, particularly those focused on reducing the environmental impact of construction. One of the most promising strategies is using green building materials, such as mass timber products (MTPs) from sustainably managed forests. These materials offer a unique benefit: the carbon absorbed during the growth of trees is stored in the harvested wood products for the duration of their service life, which can range from 50 to 80 years (Gu et al., 2021; Puettmann et al., 2021). This delayed release of sequestered carbon, especially in structural applications, makes mass timber buildings a potential carbon sink over their entire lifespan. This provides a significant advantage over traditional, fossil fuel-intensive materials like steel and concrete, positioning mass timber as a key player in sustainable construction.

Understanding a building's embodied energy through life cycle assessment (LCA) is crucial for identifying opportunities to reduce the embodied energy in new construction. LCA is an internationally accepted, science-based method that assesses the environmental impact of a product or service by quantifying the energy and materials used, as well as the emissions released to the environment at various stages of the product's life cycle (International Organization for Standardization, 2006a; International Organization for Standardization, 2006b). Conducting a LCA on functionally equivalent buildings is a widely adopted method for comparing the environmental impacts of traditional building materials versus MTPs.

Numerous studies, including those by Gu & Bergman (2018), Teshnizi et al. (2018), Simonen (2019), Jensen (2020), Chen et al. (2020), and Gu et al. (2022), have utilized LCAs to quantify the reduction in embodied carbon associated with the use of mass timber. For instance, Teshnizi et al. (2018) conducted a cradle-to-grave LCA on two high-rise student residential buildings at the University of British Columbia, Vancouver, Canada—one built with MTPs and the other with traditional building materials—and found that using MTPs resulted in 25% less global warming potential (GWP) and 18% less fossil fuel depletion compared to traditional materials. Similarly, Chen et al. (2020) conducted such comparative whole building LCAs on a high-rise mass timber building designed to be built in the Pacific Northwest of the United States, quantifying the environmental impacts with the commercial whole building LCA software Athena Impact Estimator. They observed around 20% reduction in GWP for the mass timber construction compared with concrete design structure. The Nature Conservancy led a research project comparing the mass timber buildings with functional equivalent concrete alternatives on embodied carbon reductions (Pasternack et al., 2022; Puettmann et al., 2021). Overall, the mass timber buildings at three different height levels exhibited a reduction in the embodied carbon varying between 22% and 50%.

Stakeholders are increasingly interested in understanding the precise environmental advantages of using MTPs in their specific projects, which could inform decision-making processes. Ideally, this involves comparing the LCA results of a planned mass timber building with those of a concrete or steel version with similar characteristics, such as building profiles, height, and usage patterns. The National Whole-Building Life Cycle Assessment Practitioner's Guide, developed by the National Research Council Canada

(NRC), standardizes methodologies for assessing embodied carbon in Canadian buildings. It outlines system boundaries, life cycle stages, and key building elements to ensure accurate compliance with embodied carbon reduction targets (National Research Council Canada, 2024). Moreover, Leadership in Energy and Environmental Design (LEED) Certification, provided by the U.S. Green Building Council (USGBC), further validates the sustainability of building projects. Through comprehensive evaluation, LEED certification reflects a project's environmental credentials, contributing to significant reductions in CO_2 emissions and promoting a more sustainable environment.

This study performed a Whole Building LCA on four designs of the Bakers Place project, a 14-storey mass timber-steel hybrid building built in Madison, WI, USA, using the Tally® LCA software.

5.2 Methods

5.2.1 Goal and Scope

The goal of this study was to perform a comparative cradle-to-grave Life Cycle Assessment (LCA) using the Tally® LCA tool, directly comparing the hybrid (baseline) building to functionally equivalent buildings constructed with post-tensioned concrete, full steel, and full mass timber. The baseline hybrid building was designed by the famous architect Michael Green and developed by The Neutral Project, a sustainability-focused real estate company, serving as a real-world example of sustainable building practices in North America. The environmental impacts of the four designs were analyzed using Tally®, an LCA tool developed by KT Innovations, which operates as a plug-in for Autodesk®

Revit®. Tally® enables users to extract data directly from Revit® models and apply Environmental Product Declarations (EPDs) and Life Cycle Inventory (LCI) data using the Sphera database to calculate embodied impacts. The tool is particularly valuable for architects during the early design phase, supporting informed material choices and promoting sustainability in construction.

The comparison adhered to the ISO 21930 and ISO 21931 standards (International Organization for Standardization, 2017; International Organization for Standardization, 2010). Tally® generates a comprehensive range of data comparing the environmental impacts across various categories, such as GWP, acidification, eutrophication, smog formation, ozone depletion, renewable and non-renewable energy demand. In this study, GWP was the primary impact category of interest, as it is drawn from all GHG emissions occurring throughout the life cycle of the building components and transfers the emissions to impacts toward global temperature rise. It should be pointed out that this study exclusively focused on the structural frame and did not include materials related to the building's enclosure or architectural elements.

5.2.1.1 Functional Unit and System Boundary

The functional unit for this study was defined as $1m^2$ of floor area in the designed building. ISO 21930 outlines the life cycle stages of a building enclosed in the whole building LCA study: Production, Construction, Use, and End-of-Life, as shown in Figure 1 (International Organization for Standardization, 2017). The system boundary defines which life-cycle phases are included in the analysis. The various processes that occur at each stage of a building life cycle are classified and grouped in “modules”, labeled as A1–

C4, shown in Figure 5-1. For this comparative WBLCA, the system boundary was cradle-to-grave (A-C, plus D), including Modules A1-A3, A4, B2-B5, C2-C4, and Module D. The assessment excluded Modules A5 (construction impacts), C1 (demolition), and B1 (use phase) due to either lack of data or default by the Tally® LCA tool. Operational energy impacts (B6 and B7) were also excluded from the analyzed system boundary since the study is focusing on the embodied carbon impacts of the buildings. Additionally, Tally® provides the option to include or exclude biogenic carbon in the analysis. For this study, biogenic carbon was included to accurately account for the carbon sequestered by trees and stored in the wood products during the building's operational stage and eventually release back to atmosphere or deposit in landfill, reflecting the comprehensive environmental impacts of using wood as a building material.

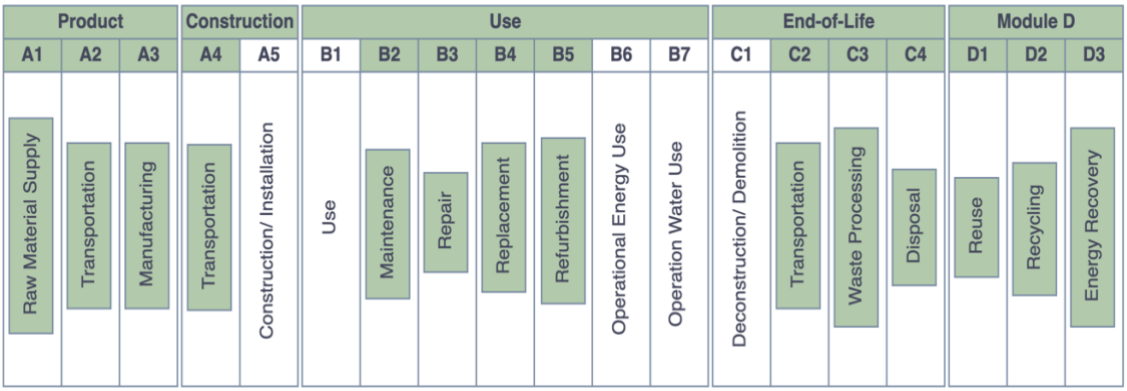


Figure 5-1: Life cycle stages and modules included (highlighted in green) using the Tally® WBLCA modelling in this study.

5.2.1.2 Bakers Place Project Overview

Bakers Place is a mixed-use development project, located in Madison, Wisconsin, USA, with a gross area of 20,850 m², and including 206 residential units. The project is distinguished by its innovative hybrid construction, combining mass timber with steel elements, alongside sustainable features such as passive house principles, LEED certification, and green roofs.

The original design, commissioned in 2020, was developed by Michael Green Architects in collaboration with Equilbrium Engineers LLC (Equilibrium) structural engineers. The building is a 14-storey structure with a 3-storey concrete podium supporting 11 stories of mass timber-steel hybrid construction. This system integrates steel columns, glulam beams, and cross-laminated timber (CLT) floors. The alternative, functionally equivalent structures designed with full mass timber, full steel, and post-tensioned concrete were meticulously designed to align with the architectural floor plan and unit layout of the hybrid baseline (Figure 5-2). Table 5-1 provides a detailed comparison of the structural designs for each scheme, highlighting the material usage, and their impacts on the building's podium.

Figure 5-2: The four structural framing systems designed for Bakers Place: Hybrid, full-mass timber, steel, and concrete (The Neutral Project LLC, 2024).

Table 5-1: Comparative Structural Aspects of Hybrid, Full-mass Timber, Concrete, and Steel Systems.

	Hybrid (Baseline)	**Full Mass timber**	**Full Steel**	**Full Concrete**
Floor-to-Floor Height	10'-9"	10'-9"	9'-7 ½"	12'-4"
Slab	CLT Floors (KLH 180mm), 5/16" sound mat, 2" Gypcrete	Same as Baseline	3½" Lightweight Concrete on top of 3" 20 ga. Steel Deck	7.5" Post Tensioned Concrete
Framing	Steel Framing and column with 1" Spray Fireproofing + Glulam Beams	Steel Framing with 1" Spray Fireproofing + Glulam columns and beams	Steel Beams, Columns, and Braced Frames with 1" Spray Fireproofing	Reinforced concrete columns, and shear walls
Fireproofing	2 layers of 5/8" Type X GWB over CLT, and 1" Spray Fireproofing for steel elements	2 layers of 5/8" Type X GWB over CLT	1" Spray Fireproofing	N/A
Impact to podium	Foundation as per Podium model in Revit (No impact relative to baseline)	Foundation as per Podium model in Revit (No impact relative to baseline)	30% increase in column cross-sectional area and 50% increase in foundation volume.	55% increase in column cross-sectional area and 100% increase in foundation volume.

5.2.2 Building Material Inventory

Four schematic-level structural scenarios, focusing solely on the major structural members for Bakers Place, were developed by the architects and engineers at Equilibrium LLC using Revit® AutoCAD software. To build material inventories of the four designs for LCA, Tally®, an application built in Revit®, converted material quantities into volumes and areas, facilitating the accurate assignment of the Environmental Product Declaration (EPD) and Life Cycle Inventory (LCI) data for all building elements. Tally® utilizes the Sphera database, the standard for reporting stages A1-A3 in EPDs for building products. For later life cycle stages, Tally® primarily relies on North American averages from its database, allowing adjustments only for the transportation stage (A4) based on specific project data. Additionally, Tally® accounts for the materials not explicitly modeled in Revit®, such as rebar within concrete assemblies, ensuring a comprehensive representation of the building's material composition. Table 5-2 lists all the materials taken off by Tally® that are used in analysis of each structural framing system of the Bakers Place.

Table 5-2: Tallies of Building Material Quantities of Each Structural Framing System of the Bakers Place.

Materials Used in Different Assemblies		Unit	Hybrid Building (Baseline)	Mass timber	Steel	Concrete
Floor and Roof	Concrete	m^3	4,648.11	4,648.11	5,188.65	8,283.98
	Lightweight Concrete	m^3	605.82	605.82	1,209.57	-
	Steel Reinforcement Rebar	kg	196,951.11	196,951.11	210,313.54	426,484.33
	Steel Welded Wire Mesh Reinforcement	kg	44,105.29	44,105.29	84,355.89	43,128.89
	Steel Deck	kg	3,222.00	3,222.00	136,064.00	-
	Cross-Laminated Timber (CLT)	m^3	2,335.23	2,335.23		-
	Steel Plate Connection	kg	12,653.00	12,653.00	19,930.00	-
	Gypsum Wall Board (GWB)	kg	347,796.00	347,796.00	-	-
Foundation	Concrete	m^3	758.82	758.82	1,138.23	1,517.64
	Steel Reinforcement Rebar	kg	18,972.56	18,972.56	28,457.92	37,944.01
	Concrete	m^3	219.28	219.28	285.05	492.80

Table 5-3: Tallies of Building Material Quantities of Each Structural Framing System of the Bakers Place. (continued)

Materials Used in Different Assemblies		Unit	Hybrid Building (Baseline)	Mass timber	Steel	Concrete
Column and Beam	Steel Reinforcement Rebar	kg	39,030.10	39,030.10	50,859.37	87,730.05
	Cold Formed Hollow Structural Steel	kg	236,946.70	155,195.90	160,134.90	1,043.00
	Hot-rolled Structural Steel	kg	291,561.23	111,535.38	541,687.58	65.69
	Spray-applied Fireproofing	kg	162,485.00	58,853.84	214,223.74	322.60
	Glue-Laminated Timber (GLT)	m^3	171.75	941.29	-	-
	Steel Plate Connection	kg	-	30,296.00	-	-
Wall	Concrete	m^3	997.31	997.31	997.31	1,458.16
	Steel Reinforcement Rebar	kg	118,671.80	118,671.80	118,671.80	173,493.80

5.2.3 Building Material Specification and Assumptions

The following building material specifications and assumptions were used in this study:

- The transportation distance for concrete was assumed to be 40 km, while mass timber components (CLT and glulam) were sourced from Austria, requiring transport by truck, boat, and train over distances of 799 km, 6,482 km, and 1,127 km, respectively. For other materials, including steel, Tally® used default industry average values.

- All materials are assumed to have the same lifespan as the building, set at 60 years.
- Regarding connections, the structural designer specified an assumption of 0.2 pounds per square foot (psf) of A36 steel for the hybrid (baseline) model. For the steel scheme, they assumed 0.15 psf of headed studs for the connections. However, since the Tally® database lacked an EPD for headed studs, it was recommended, in consultation with structural engineers, to use 0.3 psf of A36 steel plate as a substitute. These quantities were added as an accessory material to the floor system of each building scenario.
- The only EPD available for GLT in Tally® was from American Wood Council published EPD for North American glulam products, with a moisture content of 14%. However, the Wiehag GLT has a lower density of 466 kg/m³ than that published EPD (534 kg/m³), as well as a lower moisture content of 11%. To ensure accuracy in the analysis, the material take-off in Tally® was adjusted to reflect the Wiehag GLT density, rather than the default North American glulam density.

- Most concrete elements in the project, including columns, foundation, slabs on grade, and mat slabs, were located in the podium and reported as cast-in-place with 30-50% supplementary cementitious material (SCM). The National Ready Mixed Concrete Association (NRMCA) Industry-wide EPDs for cast-in-place concrete, based on the Great Lakes Midwest regional average for SCM, were used in this analysis. Since Tally® doesn't offer a specific 30-50% SCM option, the regional average was selected. Reinforcement for concrete was defined using the Concrete Reinforcing Steel Institute (CRSI)'s EPD. In the columns above the Podium, concrete strength varied by the height: 10,000 psi for floors 4-7, 7,000 psi for floors 7-10, and 5,000 psi for floors 10-Roof, with an assumed reinforcement of 178 kg/m³. The podium columns had similar reinforcement but with a concrete strength of 6,000 psi. Foundation and wall elements were designed with 4,000 psi concrete, reinforced with 25 kg/m³ and 119 kg/m³ of rebar, respectively. The slab on grade also used 4,000 psi concrete with welded wire mesh reinforcement at 20.3 kg/m², while the mat slab had a concrete strength of 6,000 psi, reinforced with 25 kg/m³ of rebar, similar to the foundation elements.

- As there is no North American industry-average EPD available for acoustic underlayment mats within Tally® database, this material was excluded from the LCA for the CLT floor systems in both the hybrid and mass timber schemes, assuming the quantity of this material would not make significant impacts to the final result (Feitel et al., 2021).

- For the post-tensioned concrete used in the podium and the overall concrete

design, structural engineers specified reinforcement with rebars at 1.75 kg per square foot and pre-stressed steel tendons at 0.8 kg per square foot. However, Tally® does not have EPD data for tendons, so an adjustment was required. The GWP of tendons, based on the Suncoast Post-Tensioning System Manufacturer-Specific EPD (Suncoast Post-Tension, 2021), is approximately 1.7 times higher per metric tonne than that of rebars, according to the Concrete Reinforcing Steel Institute (CRSI) EPD (CRSI, 2022). To account for this difference, the quantity of tendons per m^3 of concrete was calculated and then multiplied by 1.7 to reflect the higher GWP. This adjusted figure was then used in Tally® instead of the tendon data.

- A Type IV-B building requires that mass timber be protected with non-combustible material, typically Type X Gypsum Wall Board (GWB), except where it is exposed. The structural engineers specified that the exposed area of the CLT floor and attached beams must not exceed 20% of the CLT floor area in any residential unit. In Tally®, GWB was specified as an accessory material to the CLT floor, with the take-off method based on area and only the thickness of the GWB layer being adjustable. To meet the fire rating requirement of covering 80% of the CLT floor area, the required GWB volume was manually calculated by multiplying 80% of the CLT area by two layers of GWB (31.8 mm). Since Tally® does not allow assigning the required thickness to specific portion of the area, the GWB thickness was adjusted from 31.8 mm (two layers of 5/8") to 25.4 (80% of 31.8) mm to achieve the same overall volume as designed to comply the fire rating requirement. The take-off method for the

GWB, used the modeled area, an adjusted thickness of 25.4 mm and a density of 1092 kg/m³ to get the total mass (kg) of the GWB required in the designs for the LCA analysis.

Key specifications for each major material category, as defined by Equilbrium, the structural engineering company, and their Tally® database equivalents are summarized in Table 5-3.

Table 5-4: Materials specified by the architectural designs and their equivalents found in the Tally® material database.

Category	Material Specifications	Tally® Database Equivalent
Steel	Hollow structural steel (HSS) section	Cold formed HSS section + Spray-applied fireproofing (cementitious)
	Hot Rolled Steel, W and L section	Hot rolled structural steel (AISC-EPD) + Spray-applied fireproofing (cementitious)
Wood	Wiehag GLT	GLT(AWC-EPD), No finish, 534 kg/m^3 density
Concrete	Type	Cast-in-place (NRMCA-EPD)
	SCM 30-50%	Great lakes Midwest regional average
	Strength	5,000-10,000 psi
	Reinforcement	Concrete reinforcement varies in quantity per volume in different structural concrete elements.
Floor Materials	Steel Floor Assembly 3 1/2" Concrete over 3VLI Floor Deck	Lightweight, cast-in-place concrete, 3000 psi, Great lakes Midwest regional average SCM, (NRMCA-EPD) Welded Wire Mesh Reinforcement, pre-defined value (4*4, 6 ga), 3.03 kg/m^2 Steel roof and floor deck, Steel Deck Institute (SDI- EPD), 10 kg/m^2
	Mass Timber floor Assembly 5-PLY CLT (7 1/16”) 2" Gypcrete	CLT- Generic LCI data set by Tally® LCA 3000 psi, light weight concrete, 0% SCM (NRMCA- EPD), with no reinforcement

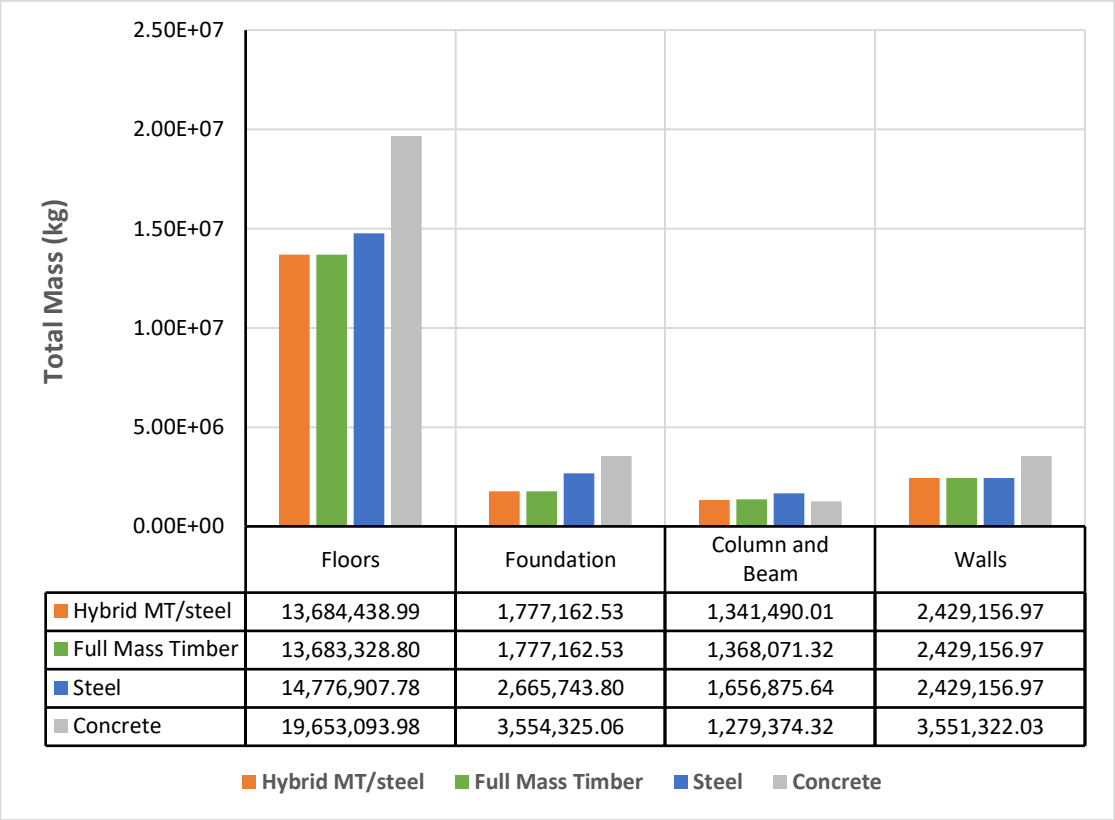
Table 5-5: Materials specified by the architectural designs and their equivalents found in the Tally® material database. (continued)

Category	Material Specifications	Tally® Database Equivalent
	5/16" Acoustic mat	No acoustic mat in the Tally® database
	Post-tensioned Concrete Slab	Cast-in-place concrete, 5000 psi, 0% SCM, (NRMCA-EPD)
	Reinforcement: 1.75 psf (rebar), 0.8 psf (tendon)	Rebar (CRSI- EPD)

5.3. Results and Discussion

5.3.1 Comparison of Building Material Mass and Relative GWP

The total mass of the major structural materials for the hybrid building, including foundations, was about 19.2 million kg, similar to the full mass timber building designed. However, the concrete and steel buildings were much heavier. The concrete building weighed around 28 million kg in total, approximately 46% more than the mass timber building, and the steel building was about 21.5 million kg, or roughly 12% heavier than the mass timber building. Figure 5-3 illustrates the mass quantities for different assemblies across the four building designs. Floors contributed most to the mass in each scenario, accounting for about 70% of the total. Notably, the floor mass in the concrete design is approximately 33% higher than the steel design and 44% more than both the hybrid and full mass timber designs. The full-mass timber and hybrid design generally had the lowest mass across all structural elements, except for columns and beams. The mass of columns and beams in the hybrid and mass timber designs is slightly higher than the concrete building but still lower than the steel design. Although the concrete design increased the cross-sectional area of columns in the podium by about 55%, compared to a 30% increase in the steel design, it utilized reinforced concrete shear walls for lateral support instead of beams. This choice eliminated the need for additional beam mass, resulting in a lower combined mass for columns and beams compared to the steel design, which had the highest total mass of these components. However, when considering all structural elements, including foundations, columns, and beams, the concrete design still had the highest overall mass.



	Floors	Foundation	Column and Beam	Walls
Hybrid MT/steel	13,684,438.99	1,777,162.53	1,341,490.01	2,429,156.97
Full Mass Timber	13,683,328.80	1,777,162.53	1,368,071.32	2,429,156.97
Steel	14,776,907.78	2,665,743.80	1,656,875.64	2,429,156.97
Concrete	19,653,093.98	3,554,325.06	1,279,374.32	3,551,322.03

Figure 5-3: Mass of different assemblies for the four different structural framing system designs.

When analyzing the relative mass of each structural material and their corresponding GWP impact across all building systems (Figure 5-4), concrete consistently stood out as the largest contributor to carbon emissions, regardless of the structural design. This is mainly because all four structural framing system designs require a substantial amount of concrete, especially in the concrete and steel scenarios. The increased volume of foundation and the columns in the podium structures of these two designs further added to the overall concrete mass. In contrast, the hybrid and full mass timber buildings, with their lighter structures, used nearly 40% less concrete than the concrete design, while the steel building used 27% less.

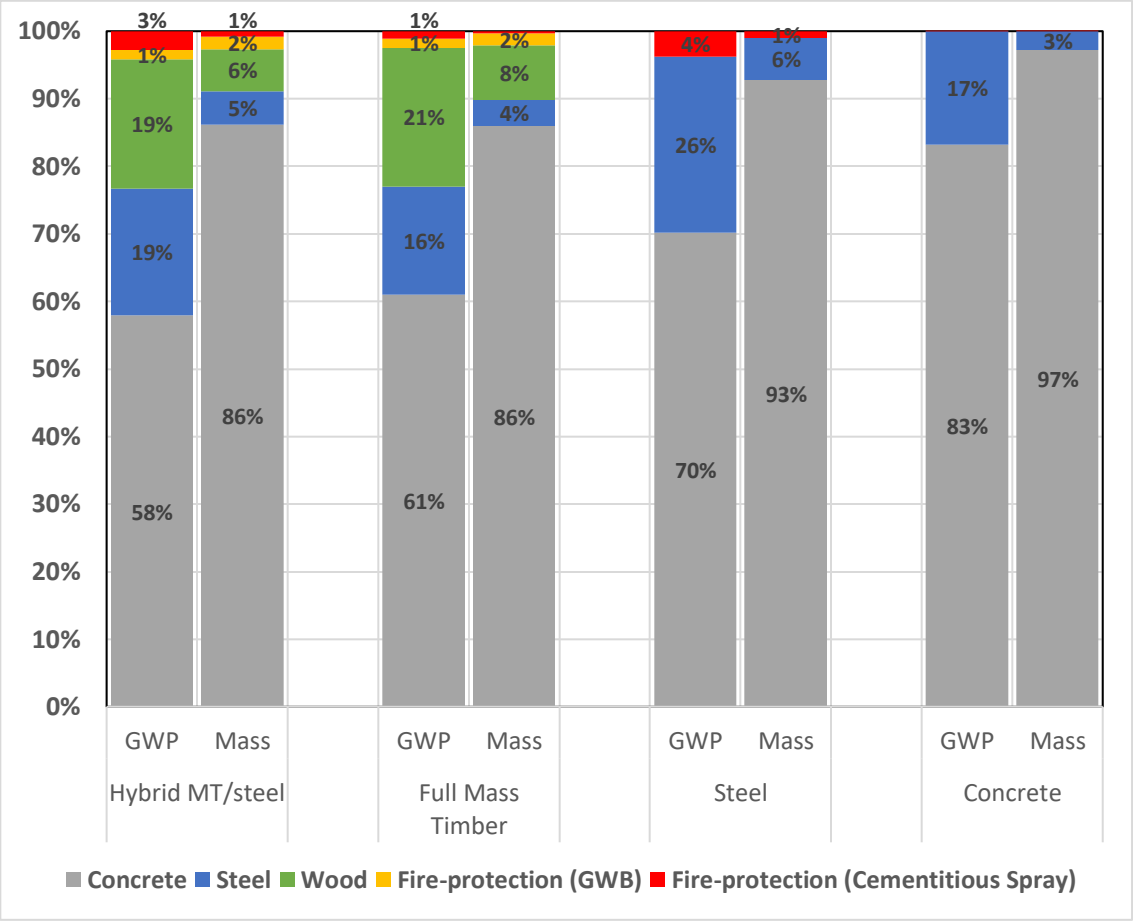


Figure 5-4: Contribution of materials to total building mass and GWPs of each structural framing system.

5.3.2 Life-Cycle Assessment Comparison for Environmental Impacts

The cradle-to-grave LCA results of the four structural framing systems based on the functional unit of 1-m^2 floor area are summarized, primarily focusing on GWP due to its significant impact on global temperature rise, compared to the other impact categories assessed by Tally®. All calculated environmental impact categories and contributions are summarized in Table 5-4. The full mass timber system outperforms the hybrid system, steel and concrete alternatives in both GWP and renewable energy use, with GWP values 1.2% lower than the hybrid system, 4.5% lower than the steel system, and 19.7% lower than the concrete system. Although the mass timber and hybrid systems required more total primary energy, they relied significantly on renewable energy compared to the steel and concrete systems, which used only 6% renewable energy. This difference is largely due to the use of mill residues as an alternative heating source and for on-site electricity generation in wood product manufacturing, particularly for drying lumber to make CLT and glulam products.

However, the steel and concrete systems outperformed the hybrid and mass timber systems in several other impact categories. This result differs from previous U.S. studies (Gu & Bergman, 2018; Chen et al., 2020), which compared the mass timber structures with traditional materials structures. These two studies found that mass timber systems not only had better performance in GWP and renewable energy use but also showed better outcomes in eutrophication and ozone depletion impacts. These differences could be attributed to the different material LCI databases and tools used in the WBLCA analysis.

Table 5-6: The cradle-to-grave environmental impacts of each framing system.

Impact Category	Unit	Hybrid	Mass Timber	Steel	Concrete
Global Warming	$kgCO_2$ eq/m^2	330.27	313.43	327.52	375.19
Acidification	kg SO_2 eq/m^2	1.53	1.64	1.12	0.99
Eutrophication	kg N eq/m^2	0.13	0.16	0.05	0.063
Smog Formation	kg O_3 eq/m^2	25.54	27.63	17.60	20.12
Ozone Depletion	CFC-11eq/m^2	1.48E-06	2.37E-06	7.49E-07	-1.74E-07
Primary Energy Demand	MJ/m^2	3290.80	3376.50	3102.37	3265.98
Non-Renewable Energy Demand	MJ/m^2	2110.10	2028.60	2915.78	3064.89
Renewable Energy Demand	MJ/m^2	1173.94	1340.95	186.36	200.43

Since the focus of the study was only on the materials in the building, no operational energy during the building occupancy was considered or modeled. Moreover, in this analysis, no impacts were observed in Modules B2-B5 (i.e., maintenance, repair, replacement, and refurbishment) despite their inclusion. This is because all materials were assumed to have a lifespan equal to the building's 60-year life, eliminating the need for maintenance or replacement. However, if finishing materials or paint had been defined for glulam or CLT components in Tally®, impacts would have been evident in these stages, such as in repair or replacement activities.

The reported environmental impacts across different life cycle stages for each building design showed major contribution from the Production Stage (see Figure 5-5 and 5-6). Exceptions are the eutrophication impacts in the full mass timber and hybrid designs exhibiting the highest contribution from the building end-of-life stage (C2-C4 stage). As shown in Figure 5, more than 50% of the eutrophication potential in the mass timber and hybrid designs occurred at the end-of-life stage, while nearly 90% and 84% the eutrophication impact in the steel and concrete designs respectively was attributed to the production stage, respectively. As noted by Chen (2019), the higher eutrophication potential is largely due to wood decomposition in landfills, which produced harmful leachates affecting aquatic systems. Since Tally® assumes that over 50% of wood is landfilled, with the significant amount of wood use in the hybrid and mass timber building scenario, this resulted in higher eutrophication impacts at the end-of-life cycle stage.

Additionally, the concrete system in this LCA study exhibited a net negative impact on ozone depletion, with 90% of this contribution occurring in Module D. This outcome could be primarily due to Tally's assumptions for steel-fabricated reinforcement in Stage D,

which include 100% scrap input. The remaining 10% of the negative value was attributed to the product stage, primarily due to the use of welded wire mesh as reinforcement in the slab-on-grade components within the building's podium. Although all building designs featured slab-on-grade components with welded wire mesh reinforcement in the podium, the steel, mass timber, and hybrid designs showed higher ozone depletion contributions in the product stage. The use of other materials with higher ozone depletion impacts, such as steel decking in the steel design and wood components in the mass timber and hybrid designs, contributed to this increase. Their high ozone depletion impacts during the product stage effectively offset the negative ozone depletion contribution from the welded wire mesh in these designs.

Moreover, the GWP contribution from the production stage was significantly lower for the mass timber and hybrid designs, as compared to the steel and concrete designs. The hybrid design showed 38% and 28% lower GWP than the steel and concrete designs, respectively. The full mass timber design demonstrated even greater reductions, with 50% and 40% lower GWP than the steel and concrete designs, respectively, at the production stage alone, which will be discussed in detail.

The increased transportation distance for mass timber products at stage 4 significantly influenced acidification and smog formation, with these impacts being approximately 10 times higher in the full mass timber and hybrid designs compared to the locally sourced steel and concrete designs. Eutrophication also increased substantially, with impacts around 5 times higher in the mass timber and hybrid designs than steel and concrete. Supporting that, a study by Gu et al. (2022) examined the environmental impacts of transporting mass timber products for a mid-rise institutional building in New Brunswick,

Canada. This study conducted a comparative cradle-to-gate LCA using SimaPro software and the TRACI impact assessment method to compare a steel frame building with an alternative mass timber design. They found that the mass timber design had higher impacts on smog formation, acidification, and eutrophication due to the longer transportation distance and increased diesel fuel consumption associated with transporting mass timber components to New Brunswick (Gu et al., 2022).

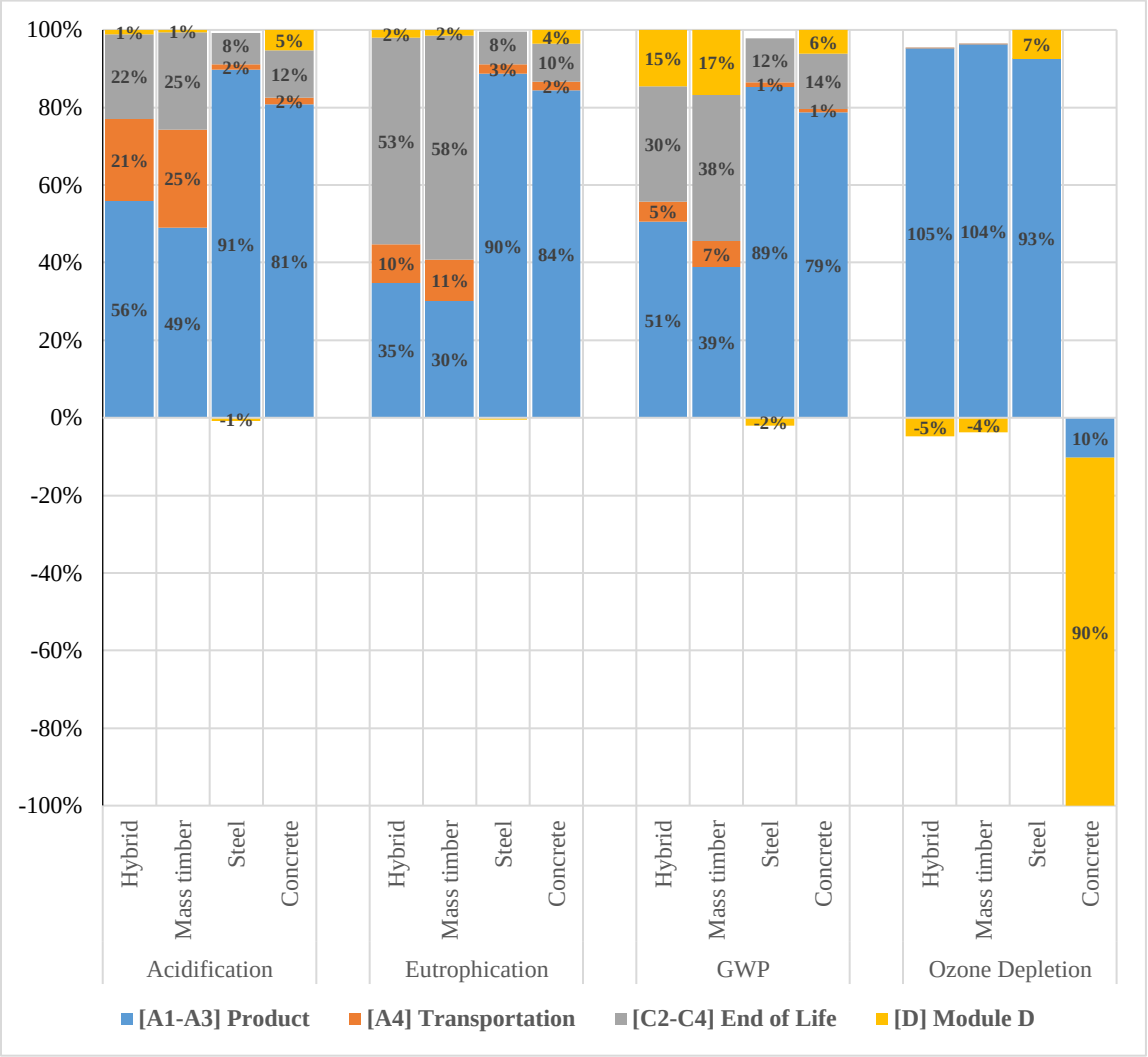


Figure 5-5: Contribution of life cycle stages to the environmental impacts and energy uses across Hybrid, Full Mass Timber, Steel, and Concrete building designs.

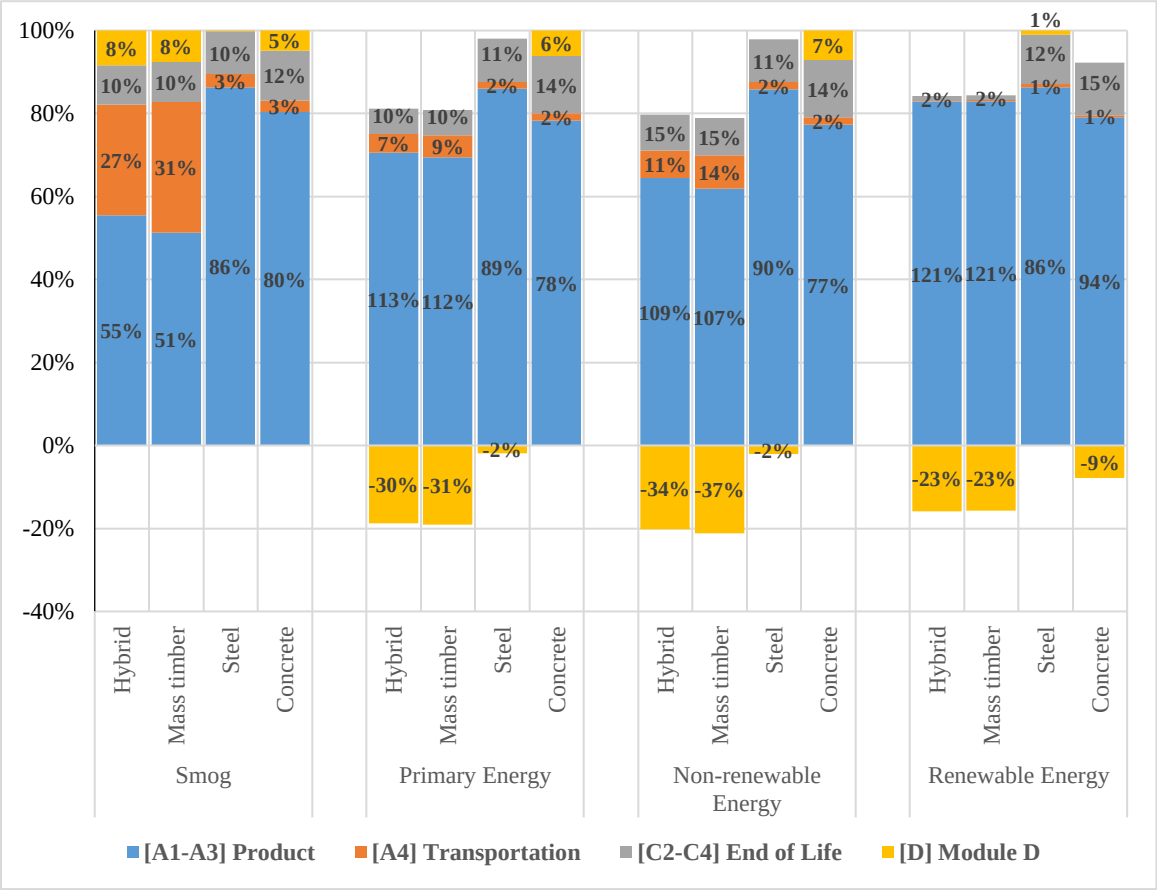


Figure 5-6: Contribution of life cycle stages to the environmental impacts and energy uses across Hybrid, Full Mass Timber, Steel, and Concrete building designs.

5.3.3 Comparison of GWP impact on different life-cycle stages

Figure 5-7 highlighted the GWP impacts of different building types across various life cycle stages. The Production Stage (A1-A3) had the highest GWP impact, particularly for concrete and steel buildings. The concrete and steel structures demonstrated similar GWPs within Stage A including modules A1-A3, with 295 and 292 CO_2 eq emission per m^2 floor area. They were about 77 and 142% higher than that of the Hybrid (167 CO_2 eq) and Full mass timber (122 CO_2 eq) building designs, respectively. The hybrid and full mass timber configurations demonstrated significantly lower GWP impacts in the Product Stage, reflecting the biogenic carbon in wood products flowing into the system as negative carbon sink. This highlights the contribution to the positive environmental impacts from the mass timber construction, since wood can store more carbon than it emits throughout the building's product stage. Tally® accounted for this benefit by incorporating it into the system at Stage A. However, this initial credit was partially offset at the End-of-Life Stage C and Supplementary beyond the boundary Stage D, where the release of stored carbon during demolition of wood products was considered. This explains why the hybrid and mass timber designs showed higher impacts in the end-of-life stage and Module D, whereas the steel building exhibited a lower impact in the end-of-life stage and achieved a net negative GWP of -7.12 kg CO_2 eq/m^2 in Module D, primarily due to Tally's assumption of a 98% recyclability rate for steel materials. Tally's method assumes that 63.5% of wood ends up in landfills, 22% is incinerated, and only 14.5% is recycled. However, the end-of-life scenarios for mass timber are likely to involve various pathways and can differ significantly across LCA software due to the uncertainties in predicting future conditions. With mass timber construction being relatively new and no buildings yet reaching the end-of-life phase, real-world data are lacking. Thus, various assumptions and scenarios in this

stage can influence the results. Tally® estimates 32% of permanent biogenic carbon storage in landfills, a conservative figure compared to the Athena Impact Estimator's 64% and the upper range of 80% suggested in other product EPDs (Kwok et al., 2019; Pak, 2020). Some studies in Australia indicated even lower decomposition rates, with softwoods and hardwoods losing only 18 and 17% of their carbon content over 46 years, respectively (Ximenes et al., 2008). These differing assumptions and uncertainties limited many studies to cradle-to-site boundaries or led them to explore multiple end-of-life scenarios, such as 100% landfill, incineration, or recycling of timber products, to assess their different environmental performances. Feitel et al. (2021) analyzed the GWP released at Stage D for different end-of-life pathways of CLT panels. They revealed that both the baseline scenario, which follows Tally's default database, and the 100% landfill scenario produced nearly identical GWP levels. However, 100% incineration emerged as the most effective option, with a GWP about 36% lower than the baseline. Conversely, 100% recycling had the highest GWP, roughly 38% higher than the baseline. They also suggested that if 100% direct reuse of CLT panels in another building cycle could happen, it could keep nearly all the stored biogenic carbon sequestered, significantly reducing the net GWP impact and enhancing carbon sequestration.

Moreover, it is important to note that the construction (A5) and deconstruction (C1) stages were excluded due to Tally's default settings. However, Chen et al. (2020) and Jolly et al. (2024) examined these stages separately and confirmed the higher GWP impact for concrete compared with the mass timber structure. Despite this, in this thesis project, when considering broader stage groupings such as (A4 and A5) or (C1-C4), mass timber still showed an overall higher GWP impact (Figure 5-7) than concrete due to significant

contributions from transportation (A4) and waste processing and disposal (C3, C4) assumptions for mass timber products. This is because, while most materials used Tally® LCA's default U.S. average transportation data, the hybrid and mass timber systems required adjustments to reflect the actual modes and distances used to deliver MTPs to the construction site. Unlike locally sourced materials like concrete and steel, the MTPs were normally transported over longer distances using multiple modes—boats, trains, and trucks, thus resulted in a higher GWP impact for these systems, emphasizing the environmental considerations of transporting materials from distant locations. Transportation impacts were minimal for the steel and concrete systems, contributing less than 1% to the total building GWP. However, for the hybrid and mass timber systems, transportation accounted for 5 and 7% of their GWP, respectively. This suggests that establishment of regional facilities for producing MTPs should be considered with an aim to reduce the transportation impacts on GWP for example.

Several studies have highlighted the benefits of locally sourcing timber to reduce CO2 emissions (Chen et al., 2020; Hemmati et al., 2024). Jolly et al. (2024) conducted a cradle-to-grave LCA study on the mid-rise mass timber construction and traditional concrete buildings in Australia and examined the transportation impacts of concrete and CLT, both locally sourced and imported from Austria. They found that the concrete building had the lowest GWP for transportation, while locally sourced timber had five times, and imported timber materials had 15 times the GWP Moreover, in a cradle-to-site comparative LCA, Liang et al. (2020) analyzed the environmental impact of transporting CLT for a 12-storey mixed-use building in Portland, OR, USA, primarily constructed from mass timber. They examined various transportation distances, ranging from local production (320 km) to

overseas sourcing from Europe (21,333 km). They found that the GWP for locally produced CLT was 3.4 kg CO_2 eq/m², which increased significantly with longer transport distances—reaching up to 47 kg CO_2 eq/m² for European sources. This underscored the substantial impact that transportation could have on the overall environmental footprint of mass timber buildings.

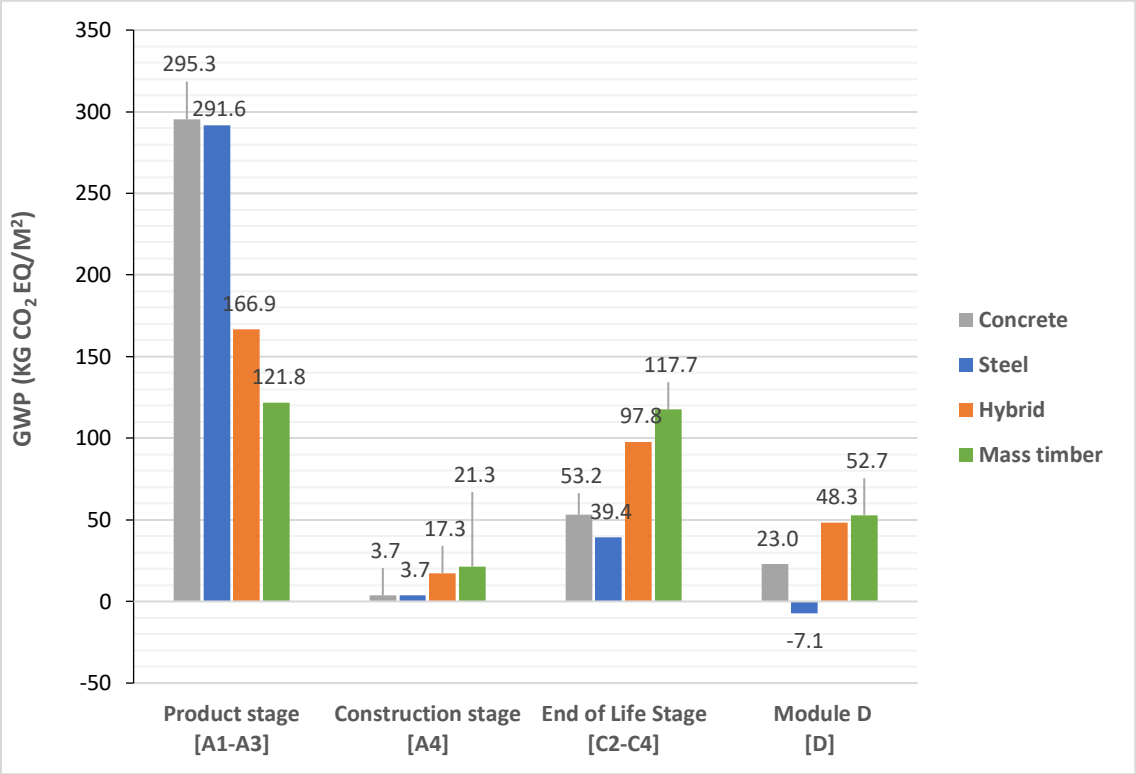


Figure 5-7: Comparison of functional unit GWP impacts over different life-cycle stages of the four building system designs.

5.3.4 Biogenic Carbon in the Buildings

Negative GWP impacts from timber products shown in the Product Stage (A1-A3) of LCAs represent the biogenic carbon sequestered by trees flow into the wood products pool. Trees absorb carbon dioxide through photosynthesis, storing approximately 50% of their dry mass as elemental carbon (Bergman et al., 2014). When a tree is harvested (Stage A1), this sequestered carbon enters the system and remains stored until the product reaches the end of its service life. In this thesis study, the carbon storage period aligns with the 60-year lifespan of the Bakers Place building.

Both the hybrid and full mass timber buildings in this study utilized 2,335.23 m^3 of CLT panels, while the hybrid design incorporated 171.75 m^3 of glulam beams and columns, and the full mass timber design included 941.29 m^3 of glulam beams and columns. The stored carbon potential of these timber components was calculated based on the biogenic CO_2 content (kg CO_2/m^3) derived from the timber products' Environmental Product Declaration (EPD). The glulam product EPD showed the biogenic carbon content of glulam is 763 kg CO_2 eq/m^3. Using this value, the total CO_2 stored in glulam beams and columns in the hybrid design was calculated as follows:

$$763\ \text{kg}\ CO_2\ \text{eq}/\text{m}^3 \times\ 171.75\text{m}^3 = 131{,}045.25\ \text{kg}\ CO_2\text{eq}$$

The CLT product EPD provided the biogenic carbon content of 762 kg CO_2 eq/m^3. According to that, the total CO_2 stored in CLT floors in the hybrid design was calculated as follows:

$$762\ \text{kg}\ CO_2\ \text{eq}/\text{m}^3 \times\ 2{,}335.23\ \text{m}^3 = 1{,}779{,}445.26\ \text{kg}\ CO_2\text{eq}$$

Thus, the total stored biogenic carbon in the hybrid design was calculated at approximately 1,910,490.5 kg CO_2, while the total stored biogenic carbon in the full mass timber design was approximately 2,497,649.5 kg CO_2. Figure 5-8 illustrates the stored biogenic carbon of each mass timber component (at Stage A) per square meter for both the hybrid and full mass timber designs, highlighting the significant carbon storage potential and environmental advantages of utilizing wood products.

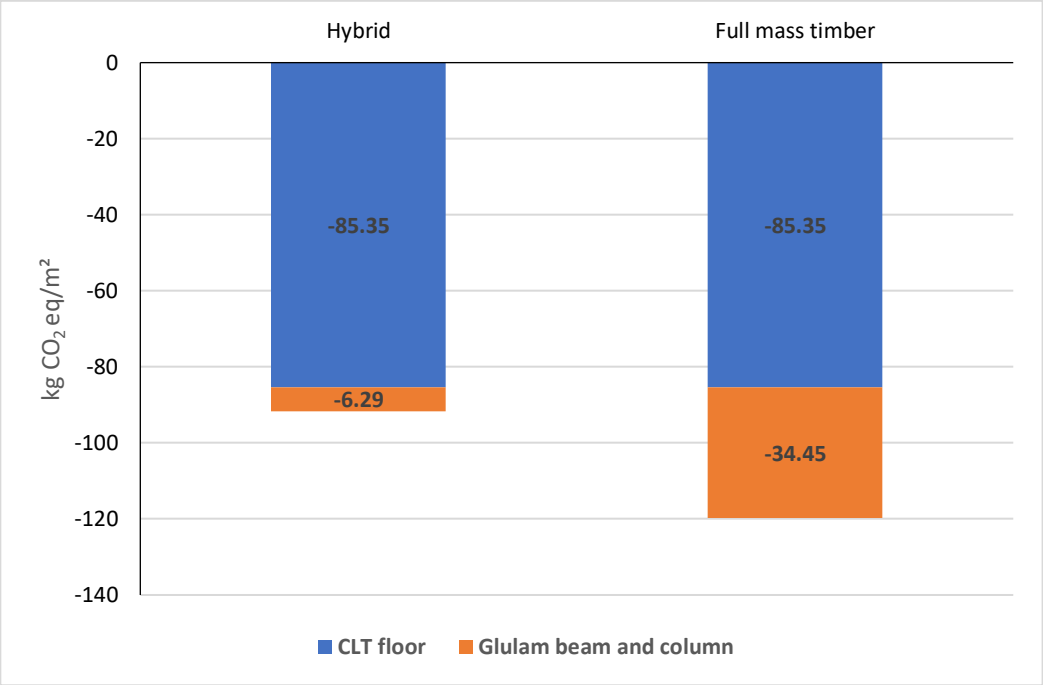


Figure 5-8: Biogenic carbon stored in the hybrid and full mass timber building designs.

5.4. Conclusions

A cradle-to-grave LCA was conducted for four high-rise building designs: Hybrid (mass timber with steel), Full mass timber, Steel, and Concrete, based on Bakers Place in Madison, WI, USA. The following conclusions were drawn from the study:

- Mass timber and hybrid designs weighed 33 and 12% less than the concrete and steel designs, respectively, significantly reducing the reliance on concrete, a major contributor to GWP.
- The hybrid design exhibited a slightly higher GWP (1%) than the steel design but showed a 12% lower GWP compared to the concrete design. The full mass timber design performed the best, with 5, 4, and 16% lower GWP than the hybrid, steel, and concrete designs, respectively.
- Full mass timber and hybrid designs had higher eutrophication impacts at the end-of-life stage, primarily due to wood decomposition in landfills. In contrast, the steel and concrete designs saw most of their eutrophication impacts occur in the production stage.
- Full mass timber and hybrid designs experienced significantly higher acidification and smog impacts, mainly due to longer transportation distances for imported timber. Conversely, steel and concrete systems benefited from local sourcing of materials.
- Mass timber and hybrid designs relied more on renewable energy sources, while steel and concrete systems heavily depended on non-renewable energy.

These findings provided valuable guidance for sustainable material choices in high-rise

buildings to address climate change.

It is recommended that the use of mass timber products be prioritized in building designs to reduce GWP. However, careful consideration should be given to sourcing materials locally to minimize transportation-related environmental impacts. Additionally, implementing strategies to manage wood decomposition at the end-of-life stage, such as enhanced recycling or alternative disposal methods, could further mitigate environmental impacts and enhance overall sustainability.

References

Architecture 2030. (n.d.). Why the built environment? Retrieved July 15, 2024, from https://www.architecture2030.org/why-the-built-environment/

Al-Ghamdi, S. G., & Bilec, M. M. (2017). Green Building Rating Systems and Whole-Building Life Cycle Assessment: Comparative Study of the Existing Assessment Tools. *Journal of Architectural Engineering*, *23*(1), 04016015. https://doi.org/10.1061/(asce)ae.1943-5568.0000222

Bergman, R., Puettmann, M. E., Taylor, A., & Skog, K. E. (2014). The Carbon Impacts of Wood Products. Forest Products Journal, 64(7/8), 220–231. https://doi.org/10.13073/FPJ-D-14-00047

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 (Switzerland), 12(11). https://doi.org/10.3390/su12114708

Chen, C. X. (2019). Environmental assessment of the production and end-of-life of cross-laminated timber in Western Washington (Doctoral dissertation, University of Washington). University of Washington Libraries.

Concrete Reinforcing Steel Institute (CRSI). (2022). Industry-wide environmental product declaration (EPD). Retrieved from https://www.crsi.org/wp-content/uploads/CRSI_Industry-Wide_EPD_Sep2022.pdf

Feitel, A., Redwine, B., Kingsley, G. (2021). Think Wood, WoodWorks _Wood Products Council. Chrome

extension://efaidnbmnnnibpcajpcglclefindmkaj/https://www.nordic.ca/data/files/publication/mul ilang_file/Platte15LCACaseStudy_July2021_KLA.pdf

Gu, H.; Liang, S.; Pierobon, F.; Puettmann, M.; Ganguly, I.; Chen, C.; Pasternack, R.; Wishnie, M.; Jones, S.; Maples, I. (2021). Mass Timber Building Life Cycle Assessment Methodology for the U.S. Regional Case Studies. Sustainability 2021, 13, 14034. https://doi.org/10.3390/su132414034

Gu, Chang & Gu, Hongmei & Gong, Meng & Blackadar, Janet. (2022). A Case Study on the Impact of Transportation of Mass Timber Products on the Cradle-to-Gate LCA Results for an Institutional Building. Recent Progress in Materials. 4. 1-1. 10.21926/rpm.2203014.

Gu, H., Nepal, P., Arvanitis, M., & Alderman, D. (2022). Carbon Impacts of Engineered Wood Products in Construction. IntechOpen. doi: 10.5772/intechopen.99193

Gu, H., & Bergman, R. (2018). Life cycle assessment and environmental building declaration for the design building at the University of Massachusetts. Retrieved from fs.usda.gov/treesearch: https://doi.org/10.2737/FPL-GTR-255

Harte, A. M. (2017). Mass timber – The emergence of a modern construction material. Journal of Structural Integrity and Maintenance, 2(3), 121-132.

Hemmati, Mahboobeh & Messadi, Tahar & Gu, Hongmei & Seddelmeyer, Jacob & Hemmati, Moein. (2024). Comparison of Embodied Carbon Footprint of a Mass Timber Building Structure with a Steel Equivalent. Buildings. 14. 1276. 10.3390/buildings14051276.

International Organization for Standardization. (2006a). ISO 14040: Environmental management—Life cycle assessment—Principles and framework. ISO.

International Organization for Standardization. (2006b). ISO 14044: Environmental management—Life cycle assessment—Requirements and guidelines. ISO.

International Organization for Standardization. (2017). Sustainability in buildings and civil engineering works – Core rules for environmental product declarations of construction products and services; ISO 21930:2017.

International Organization for Standardization. (2010). Sustainability in building construction — Framework for methods of assessment of the environmental performance of construction works; ISO 21931-1:2010.

IPCC (Intergovernmental Panel on Climate Change). 2021. Climate change 2021: The physical science basis. Working Group I contribution to the IPCC Sixth Assessment Report. Cambridge, United Kingdom: Cambridge University Press. www.ipcc.ch/assessment-report/ar6.

Jensen, A. S. (2020). Mass Timber Solutions for Eight Story Mixed-Use Buildings: A Comparative Study of GHG Emissions. Retrieved from www.preprints.org: https://www.preprints.org/manuscript/202007.0175/v2

Jolly, R., Fairweather, H., Rayburg, S., & Rodwell, J. (2024). Life cycle assessment and cost analysis of mid-rise mass timber vs. concrete buildings in Australia. Sustainability, 16(15), 6465. https://doi.org/10.3390/su16156465

Kwok, A. G., Zalusky, H., Rasmussen, L., Rivera, I., & McKay, H. (2019). Cross-laminated timber buildings: A whole building life cycle assessment case study series. TallWood Design Institute. https://tallwoodinstitute.org

Liang, S., Gu, H., Bergman, R., & Kelley, S. S. (2020). Comparative life-cycle assessment of a mass timber building and concrete alternative. Wood and Fiber Science, 52(2), 217–229. https://doi.org/10.22382/wfs-2020-019

National Research Council Canada. (2024). National Whole-Building Life Cycle Assessment Practitioner's Guide: Guidance for Compliance Reporting of Embodied Carbon in Canadian Building Construction. https://nrc-publications.canada.ca/eng/view/ft/?id=533906ca-65eb-4118-865d-855030d91ef2&dsl=en

Pak, A. (2020). Biogenic carbon storage accounting in WBLCA. YouTube. https://www.youtube.com/watch?v=7XTzKESNGEU

Pasternack, R.; Wishnie, M.; Clarke, C.; Wang, Y.; Belair, E.; Marshall, S.; Gu, H.; Nepal, P.; Dolezal, F.; Lomax, G.; et al. What Is the Impact of Mass Timber Utilization on Climate and Forests? Sustainability 2022, 14, 758. https://doi.org/10.3390/su14020758

Puettmann, M.; Pierobon, F.; Ganguly, I.; Gu, H.; Chen, C.; Liang, S.; Jones, S.; Maples, I.; Wishnie, M. (2021). Comparative LCAs of Conventional and Mass Timber Buildings in Regions with Potential for Mass Timber Penetration. Sustainability 2021, 13, 13987. https://doi.org/10.3390/su132413987

Sartori, I., & Hestnes, A. G. (2007). Energy use in the life cycle of conventional and low-energy buildings: A review article. *Energy and Buildings*, *39*(3), 249–257. https://doi.org/10.1016/j.enbuild.2006.07.001

Simonen, K. H. (2019). Life Cycle Assessment of Katerra's Cross-Laminated Timber (CLT) and Catalyst Building. Seattle: Carbon Leadership Forum and the Center for International Trade in Forest Products at the University of Washington.

Suncoast post-tension. (2021). Environmental product declaration (EPD): Post-Tensioning Strand. Retrieved from https://cdn.scscertified.com/products/cert_pdfs/SCS-EPD-06741_Suncoast-PT_PT-Strand_030121.pdf

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(May), 172–177. https://doi.org/10.1016/j.procir.2017.11.121

The Neutral Project LLC. (2024). Bakers Place Case Study: A comparative exploration into mass timber and conventional construction methods. USDA Wood Innovations Grant Program. https://www.theneutralproject.com

Ximenes, F., Gardner, W., & Cowie, A. (2008). The decomposition of wood products in landfills in Sydney, Australia. Waste Management, 28(8), 2344-2354. https://doi.org/10.1016/j.wasman.2007.11.006

6 General Conclusions and Recommendations

6.1 General Conclusions

This thesis contains 6 chapters, with chapters 3, 4 and 5 serving as the key chapters for the work conducted.

Chapters 3 and 4 present the results from the investigation on the environmental impact of Lumber Production in New Brunswick. By conducting cradle-to-gate Life Cycle Assessment (LCA) on softwood and hardwood lumber production, the following conclusions were drawn:

Softwood lumber production encompassed harvesting and product stages, including sawing, kiln drying, and planing, with a GWP of 43 kg CO_2 eq/m^3 and a total energy consumption of 2,377 MJ/m^3, 50% of which was derived from wood residues as renewable sources. In contrast, the hardwood LCA was limited to the sawing stage, excluding kiln drying and planing. Although hardwood showed a lower GWP of 41 kg CO_2 eq/m^3, this figure reflects only the harvesting and sawing stages. When these stages in softwood were compared directly, hardwood exhibits significantly higher emissions, particularly in the sawing process. Hardwood production consumes 736 MJ/m^3 of energy, with only 2% from renewable sources, mainly due to the exclusion of kiln drying, which typically utilizes a substantial share of renewable energy. Furthermore, hardwood demonstrates higher impacts on smog (+68%), acidification (+63%), and eutrophication (+40%), driven by its denser material, longer transportation distances, and energy-intensive sawing process. Both softwood and hardwood lumber act as significant carbon sinks, storing 17 and 24 times their respective cradle-to-gate CO_2 emissions, highlighting their potential for climate

change mitigation in construction. and highlights the critical roles of softwood and hardwood in sustainable construction.

Chapter 5 provides the findings from a comparative WBLCA of the Bakers Place project, evaluating the environmental impacts of four structural materials used in building design. This study highlights both the environmental benefits and challenges of using mass timber and hybrid mass timber-steel systems compared to concrete and steel structures:

The full mass timber design achieved the lowest GWP, reducing emissions by up to 16% compared to concrete and significantly lowering non-renewable energy demand by 30% relative to steel and concrete structures. The hybrid design also demonstrated a lower GWP than concrete, though it was 1% higher than steel. These findings underscore the potential of timber systems in reducing embodied carbon. Additionally, mass timber's substantial biogenic carbon storage capacity reinforces its critical role in mitigating climate change. While mass timber and hybrid systems excel in reducing GWP and promoting renewable energy use, they exhibit higher impacts in acidification, eutrophication, and smog formation. These challenges are primarily attributed to long transportation distances for imported timber and the release of stored carbon at the end of life. Addressing these issues through localized sourcing and improved end-of-life management will be essential for enhancing the sustainability of mass timber in construction.

6.2 Recommendations and Future Research

To improve the sustainability of lumber production and encourage its widespread adoption, it is critical to enhance local energy generation using wood residues, particularly

for electricity in sawmills, to reduce dependency on grid electricity. Moreover, developing and implementing end-of-life strategies, such as recycling, reuse, and energy recovery, can significantly mitigate carbon release and other environmental impacts associated with timber disposal in landfills and reduce the GWP of mass timber buildings during their end-of-life stage.

The following aspects of further research would help understand the environmental impact of lumber production in New Brunswick and the mass timber-steel hybrid building case study of Bakers Place:

Conduct cradle-to-grave LCAs on lumber applications in building types more common in New Brunswick, such as low-rise structures and single-family homes.

Investigate the end-of-life stage of wood products in New Brunswick to establish a region-specific database, improving insights into disposal methods and impacts.

Enhance the establishment of local or regional facilities for producing mass timber products to reduce transportation distances and their associated environmental impacts.

Curriculum Vitae

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Publications:

Gu C, Gu HM, Gong M, Blackadar J, and Zahabi N. 2024. Comparison of using two LCA software programs to assess the environmental impacts of two institutional buildings. *Sustainable Structures* 4 (1): 000034. DOI: 10.54113/j.sust.2024.000034.

Zahabi, N., Gong, M., Gu, H., & Blackadar, J. Case Study on the Cradle-to-Gate Life Cycle Assessment of Softwood Lumber Production in New Brunswick, Canada. *Sustainable Forestry*. (Under Review).

Zahabi, N., Gong, M., Gu, H., & Blackadar, J. Case Study on the Cradle-to-Gate Life Cycle Assessment of Hardwood Lumber Production in New Brunswick, Canada. *Buildings*. (Under Review).

Zahabi, N., Gu, H., Gong, M., & Blackadar, J. Comparative Whole Building Life Cycle Assessment on the Four Framing Systems of the Bakers Place using Tally® LCA Tool. (In Preparation).

Conference Presentations:

Zahabi, N., Gong, M., Gu, H., & Blackadar, J. 2024. Comparative Whole Building Life Cycle Assessment of the Baker's Place using Tally LCA Tool. Poster presentation at the 67th International Convention of the Society of Wood Science and Technology (SWST), June 30-July 5, Portoroz, Slovenia (Poster ID #: 211).

Zahabi, N. (2024). Case studies on the cradle-to-gate life cycle assessment of softwood lumber production. Oral presentation at the Science Atlantic Environmental Conference (SAEC), March 23. Charlottetown, PEI, Canada.

Zahabi, N. (2024). Case studies on the cradle-to-gate life cycle assessment of softwood lumber production. Oral presentation at the 30th Graduate Research Conference 2024: Science and Engineering Stream, March 25. The University of New Brunswick, Fredericton, Canada.