CROSS-LAMINATED TIMBER BUILDINGS: A WBLCA CASE STUDY SERIES

TALLWOOD DESIGN INSTITUTE

Net ZED Case Study Lab

CLT BUILDINGS: A WBLCA CASE STUDY SERIES

five whole building life cycle assessment case studies

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Disclaimer
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3 image of Carbon12 ©Andrew Pogue 4 image of District Office courtesy of Hacker 5 image of CLTHouse ©Lara Swimmer Photography

WBLCA of CLT Buildings

Embodied & Biogenic Carbon

Executive Summary

This series highlights five **whole building life cycle assessments** (WBLCAs) of buildings incorporating the building material known as cross-laminated timber (CLT) into some or all of their structure, using a primary cradle-to-grave system boundary. This case study series will serve as an educational resource for academics, professionals, and CLT project stakeholders. While there is some uncertainty about the best way to reduce greenhouse gas emissions from architecture and construction, using CLT and other wood building materials is one possible means to reduce the emissions associated with a building's materials. When forests are managed sustainably, wood construction materials can contribute to climate change mitigation goals as an indefinite carbon store and as a replacement of other fossil-fuel intensive materials. WBLCA is an assessment method to estimate the environmental impacts of buildings; this series offers insight into the current possibilities and limitations of WBLCA for CLT buildings. The series begins with background information on WBLCA methods and CLT, a review of previously published CLT building WBLCAs, and a life cycle assessment of an individual CLT wall element using the WBLCA softwares Tally® and Athena Impact Estimator for Buildings (Athena IE).

The five buildings in the case study series are an office building in Portland, Oregon, a multi-family residential building in Portland, Oregon, a single-family residential home in Seattle, Washington, an industrial facility in Pemberton, British Columbia, and a parking

Whole building life cycle assessment (WBLCA) *is a method to quantify and evaluate the environmental impacts associated with a building's life cycle.*

garage in Springfield, Oregon. Each case study contains three parallel WBLCA results for the same building. Two results come from Tally — one including biogenic carbon and one excluding biogenic carbon — and the third result comes from Athena IE. Each of the three WBLCAs estimates impacts with a cradle-to-grave system boundary of life cycle modules A through C, as well as a cradle-to-cradle system boundary of life cycle modules A through D (benefits beyond the system boundary). Thus, each case study includes six result sets. Case studies 1, 2, and 3 have a WBLCA scope of the building's structure and foundations, but case studies 4 and 5 have a WBLCA scope that includes structure, foundations, enclosure, interior partitions, and finishes.

Across all the case studies, it was found that the total global warming potential per square meter of built space varies widely between tools (Athena IE and Tally) as well as between system boundaries (life cycle modules A through C or A through D) and biogenic carbon considerations. Other environmental impact categories were sensitive to the selected software and system boundary, but were generally not affected by biogenic carbon inclusion or exclusion.

Variations arise from differences between Tally and Athena IE's methodologies (especially relating to carbon sequestration and end-of-life scenarios for wood building materials), as well as from software characteristics that prevent recreating the identical materials in the programs. Despite variations between tools, each tool is a viable resource for WBLCA practitioners. By their nature, WBLCAs are approximations that should not be viewed as definitive or exact representations of a building's environmental impacts.

Introduction to Embodied Carbon

Whole building life cycle assessment is a tool that can help estimate the environmental impacts of the built environment, especially those that directly affect climate change. Globally, industries and countries have been working toward solving the climate change crisis. Serious international efforts began in 1992 with the creation of the organization and environmental treaty called the United Nations Framework Convention on Climate Change (UNFCCC), followed by the **Kyoto Protocol Agreement** in 2008 and the **Paris Agreement** in 2016. To meet agreement goals, participants must reduce greenhouse gas emissions and bolster the storage of greenhouse gases (such as carbon dioxide) in carbon "sinks" — chiefly forests and oceans (UNFCCC, 2018).

Reducing greenhouse gas emissions amidst anticipated population growth is a key challenge. Extensive construction will accompany population growth — global built floor area will likely grow by 230 billion m^2 by 2060, essentially doubling the existing building stock (International Energy Agency, 2017, p. 126).

The architecture and construction industry's response to climate change includes, but is not limited to, the 2030 Challenge, issued by **Architecture 2030**, and the AIA 2030 Commitment. Both initiatives seek to make all new buildings and renovations Zero-Net-Carbon (ZNC) by 2030. A ZNC building produces on-site or procures off-site 100% of its energy demands through carbon-free renewable energy sources (Architecture 2030, 2018). As the building sector approaches this ambitious goal, the environmental impacts associated with a building's operational energy use decreases towards zero, and the relative portion associated with the building's materials increases. The greenhouse gas emissions associated with the extraction, construction, use, and disposal of a building's materials are often referred to as "**embodied carbon**."

Figure 1 illustrates four primary pathways in which forests and wood products can help reduce embodied carbon and mitigate climate change: the forest pathway, storage pathway, energy pathway, and avoidance pathway (based on Oliver, Nassar, Lippke, & McCarter, 2014). Numerous studies have analyzed how wood construction materials, through combinations of these strategies, can potentially reduce a building's embodied carbon. In a meta-analysis of 66 papers, Sathre and O'Connor note that, in all studies, the production of wood-based materials requires less greenhouse gas emissions than

*The first **Kyoto Protocol Agreement,** signed by 37 industrialized countries in 2008, targeted an average 5% reduction of greenhouse gas emissions for the years of 2008–2012 (Chau, Leung, & Ng, 2014).*

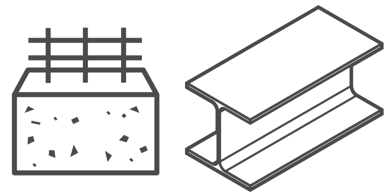
The Paris Agreement *signed in 2016, represents the commitment of 55 parties, primarily countries, to keep the global temperature rise below a 2° C increase from preindustrial levels (UNFCCC, 2018).*

Architecture 2030 *is a non-profit organization dedicated to reducing greenhouse gas emissions of the built environment.*

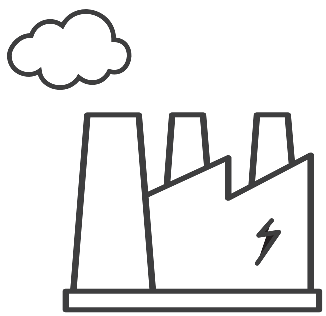
Embodied carbon *is also known as embodied greenhouse gases or carbon footprint.*

Ways that Forests & Wood Products can Mitigate Climate Change

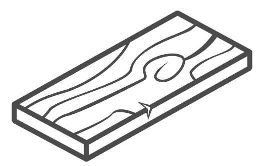
Forest Pathway
In the standing forest, trees remove CO_2 from the atmosphere and sequester it as carbon within plant tissues and in the soil.



Avoidance Pathway
If wood product manufacturing results in less emissions than a comparable product, then substituting wood those products will consume fewer fossil fuels and emit less CO_2.



Energy Pathway
While burning wood for energy emits CO_2, it also displaces the CO_2 produced by the burning of fossil fuels. In a landfill, wood can also produce energy when it decomposes into landfill gas if this landfill gas is captured for energy. Regrowth of the forest can reabsorb some of the CO_2 emitted in combustion.



Storage Pathway
Carbon contained in wood products is stored throughout the product's life. If the product is eventually landfilled, a portion of the carbon will remain stored and may continue to be stored for hundreds of years. Reusing wood products can extend the carbon storage without the potent methane emissions of landfill decomposition.

Figure 1 Wood Pathways, categories modified from Oliver et al., 2014

the production of steel and concrete alternatives (2010). Including the entire life cycle of wood products, most of the 66 studies display lower total emissions for wood products (Sathre and O'Connor, 2010). Overall, they assert that substituting wood for other products may reduce greenhouse gas emissions where forests are sustainably managed and allocated to efficient products, such as CLT.

Introduction to Cross-Laminated Timber

Traditionally, wood products have been unable to compete with the structural characteristics of steel and concrete. The development of layered engineered wood products known as "mass timber" or "solid timber" has given the building industry viable alternatives to steel and concrete construction (Post, 2015). As a building material, mass timber materials have potential benefits such as carbon sequestration, prefabrication potential, natural aesthetic, and a lower density than steel and concrete. Cross-laminated timber is one of these alternatives. Cross-laminated timber (**CLT**) is "a prefabricated engineered wood product consisting of at least three layers of solid-sawn lumber or structural composite lumber where the adjacent layers are cross-oriented and bonded with structural adhesive to form a solid wood element" (American Wood Council, 2018, p. 60).

__CLT__ was developed in the 1990s in central Europe (Karacabeyli & Brad, 2013). CLT is now a well-established building material in Europe and has been gaining popularity in North America and worldwide as CLT manufacturing facilities spread outside Europe in the 2010s (Grasser, 2015).

CLT (figure 2) can be a structural or non-structural material, suitable for walls, floors, ceilings, stairs, and roofs. Due to the cross orientation of layers, CLT has a structural capability of a two-way span, desirable for floor applications (Karacabeyli & Brad, 2013).

In North America, the spread of CLT use has been aided by the development of a reputable performance-based product standard for structural CLT in 2012: ANSI/APA PRG 320-2012 Standard for Performance-Related Cross Laminated Timber. Developed by APA – The Engineered Wood Association, the standard establishes size and performance requirements for seven CLT performance grades. This standard is referenced in several North American standards — the 2015 National Design Specifications (NDS) for Wood Construction in the United States and the 2014 Canadian National Standard for Engineering Design in Canada (CSAO86) (Pei et al., 2016).

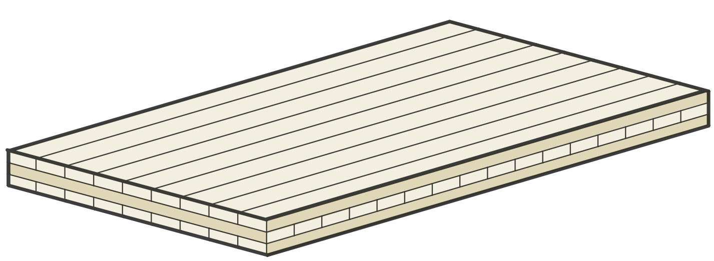


Figure 2 Cross-Laminated Timber Panel Diagram

Partly thanks to these reference standards, the 2015 edition of the National Building Code of Canada (NBCC) and the 2015 International Building Code (used throughout much of the United States) incorporated approval for some uses of CLT. In the United States, CLT is code-approved for structural use in gravity systems (e.g. floors, beams, columns, load-bearing walls) as a heavy timber material for buildings up to 85 ft tall (Mayo, Blomgren, Jones, Richardson, & Hackett, 2018). However, using CLT for lateral, seismic force resisting systems, as defined by the IBC, currently requires the performance-based alternative means and methods for approval (Mayo et al., 2018). The 2021 International Building Code will expand the options for approved code usage of CLT.

The first CLT manufacturers in North America were Nordic (established in 2010 in Quebec), Structurlam (established in 2011 in British Columbia), Smartlam (established in 2012 in Montana), and D.R. Johnson (established in 2015 in Oregon). Since then, several new CLT manufacturers have begun operation or have facilities planned.

Cross-laminated timber production begins with the growth of wood in managed forest stands. Common wood species used in North American CLT are spruce, pine, fir, and larch; these species are often combined together in a single panel as spruce-pine-fir and Douglas fir-larch. Forest processes such as site preparation, planting seedlings, fertilization, thinning, and harvest require fuel and fertilization inputs. Harvested wood is transported to a lumber yard via a diesel-fueled truck, where it is sawed, sorted, and dried. After processing, trucks and possibly trains transport the wood to a CLT manufacturing facility.

At the CLT facility, the lumber is further dried to 12 percent (+/- 3%) moisture, oven dry basis, then is planed and sorted based on grade (Karacabeyli & Brad, 2013). To produce the long lengths of CLT panels, the lumber is vertically finger jointed using a resin. Then, lumber pieces are arranged on alternating layers, and resin is applied between the layers. The 3, 5, or 7-layer panels are pressed together and any alterations or openings are cut with a CNC machine. After completion, the panels are packaged and shipped.

Figure 3 illustrates the environmental inputs and outputs associated with the manufacturing of CLT as typically assessed in an LCA.

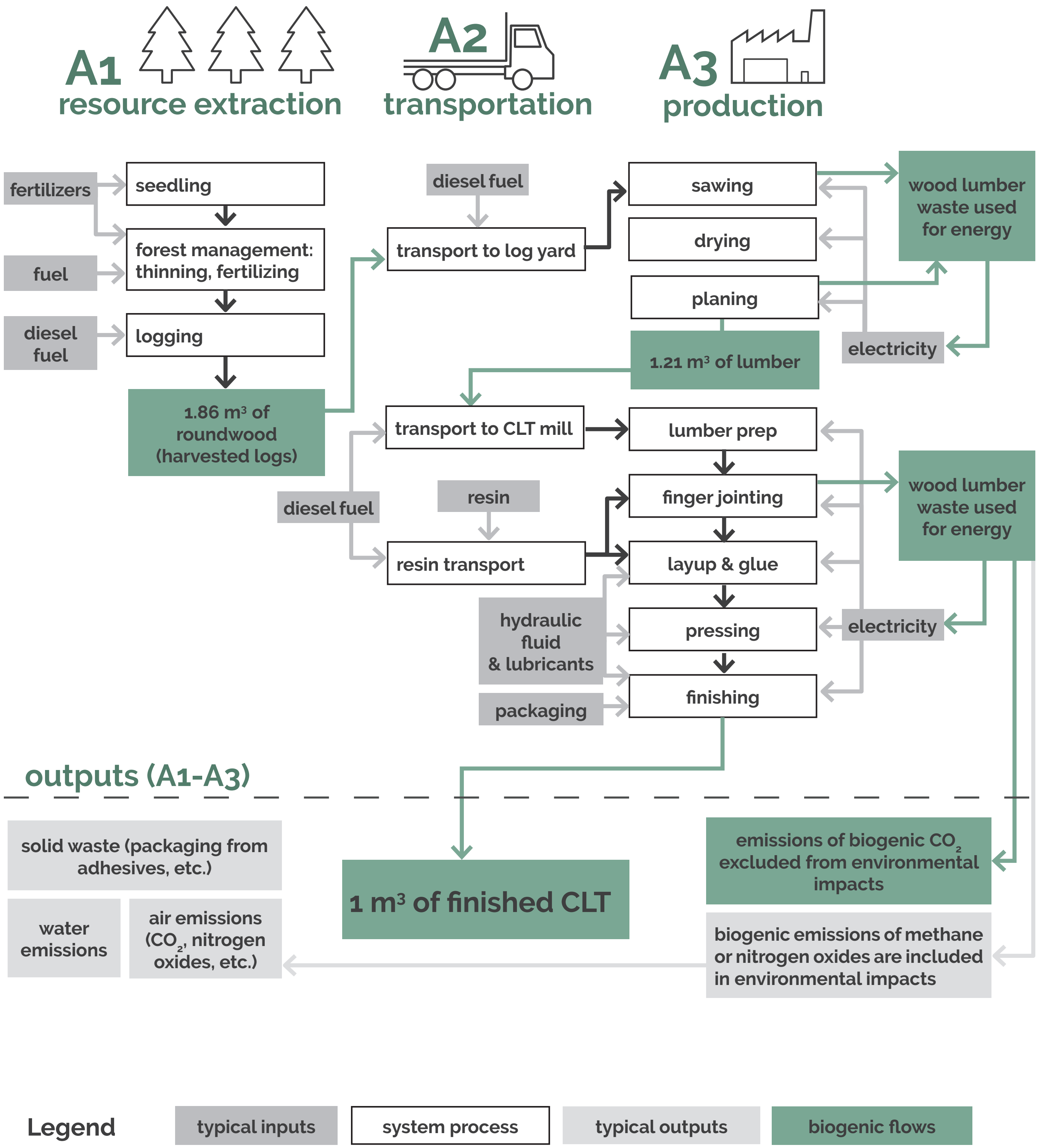


Figure 3 Cross-Laminated Timber Production Process

Whole Building Life Cycle Assessment

The environmental impacts of CLT can be studied at a material level or at the scope of a whole building. A life cycle assessment (LCA) evaluates the environmental impacts of a single product or service, such as a specified quantity of CLT. Some CLT manufacturers publish the LCA information for their product in a formal, third-party verified document known as an environmental product declaration (EPD). A whole building's environmental impacts are generally estimated through a process known as whole building life cycle assessment (WBLCA). A WBLCA takes life cycle assessment or inventory data from multiple materials and aggregates them to evaluate impacts from a building's life cycle, "including material production, construction processes, building use (operation), and end-of-life activities" (Athena Sustainable Materials Institute, 2017). By quantifying the environmental impacts of buildings, this process may help designers and stakeholders reduce the environmental impacts of buildings, including embodied carbon.

Shown in figure 4, whole building life cycle assessment is an integrated process that includes a definition of the assessment's goals and scope, a life cycle inventory, a life cycle impact assessment, and an interpretation of the results. The goal and scope define the assessment's purpose, physical scope, and chronological system boundary — the life cycle stages to be included in the assessment. The life cycle inventory phase documents the quantities of inputs and outputs to the product system. Inputs are consumed resources such as water, fuel, and electricity. Outputs are the emissions back to the environment — air emissions like greenhouse gases, water emissions, and solid waste emissions. The impact assessment phase takes the information from the inventory phase and assesses the environmental impacts in terms of **impact categories**.

Impact category
"class representing environmental issues of concern to which life cycle inventory analysis results may be assigned" (ISO 14044, 2006)

In North America, the impact categories typically used are those outlined in the US Environmental Protection Agency's Tool for the Reduction and Assessment of Chemical and other Environmental Impacts (TRACI) methodology: global warming potential, acidification potential, human health particulate, ozone depletion potential, smog potential, and eutrophication potential (Bare, 2012). Although not a part of TRACI, many WBLCAs also report the embodied energy of a building, which is a measure of the energy to produce, transport, construct, and demolish materials. Embodied energy often correlates to greenhouse gas emissions, but it does not always. For example, when product manufacturing energy comes from on-site solar, it

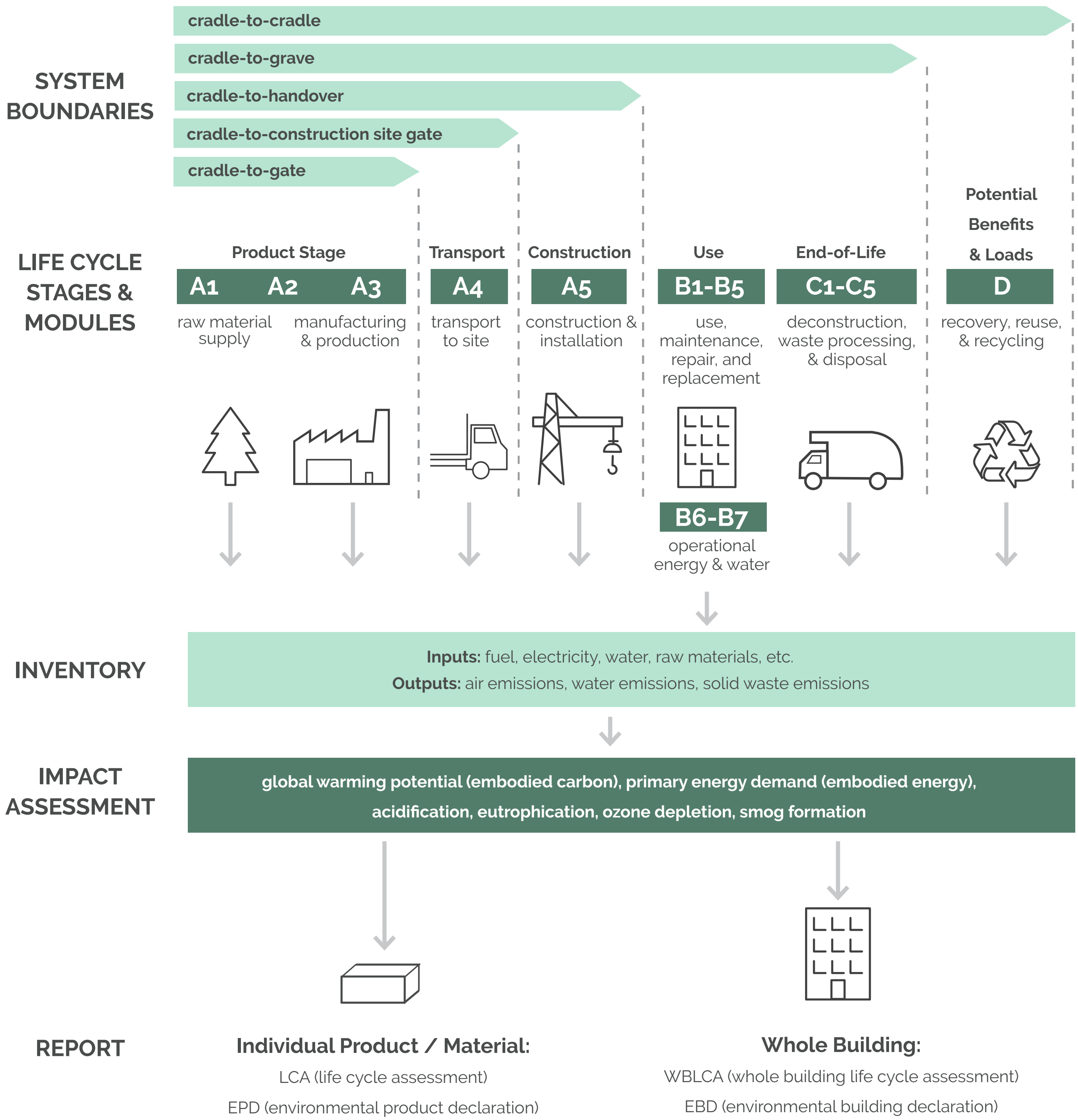


Figure 4 Life Cycle Assessment and Whole Building Life Cycle Assessment

may have a high embodied energy but will have relatively low global warming potential.

Global warming potential measures the sum of greenhouse gas emissions over a specified time period. In an LCA or WBLCA, global warming potential is measured by kilograms of CO_2 equivalent (kg CO_2 eq), usually over a 100 year time span, This impact category encompasses the emissions of CO_2 as well as other greenhouse gases: CH_4, N_2O, SF_6, PFC and HFC, which are converted into the quantity of CO_2 that would lead to the equivalent amount of global warming potential (IPCC, 2014).

Global warming potential expresses the embodied carbon, also known as embodied greenhouse gases, or carbon footprint. Embodied carbon includes all greenhouse gas emissions from one or more life cycle stages of a product; and for building materials, typically excludes the emissions during the operational/use phase of a building (Lützkendorf & Balouktsi, 2016, p. 16). The general term "embodied carbon" is often used, which can cause confusion when the life cycle stage system boundary is not explicit.

Embodied carbon can be defined by which life cycle stages are included. *Initial embodied carbon* usually refers to the carbon emissions associated with life cycle modules A1 through A5: raw materials, production, transportation, and construction. This may also be referred to as the embodied carbon from cradle-to-handover. *Recurring embodied carbon* comes from life cycle modules B1 through B5: installed product in use (B1), maintenance (B2), repair (B3), replacement (B4), and refurbishment (B5). Less commonly, recurring embodied carbon sometimes includes **operational carbon** from energy and water use, which is stages B6 and B7. *End-of-life embodied carbon* comes from life cycle modules C1-C4: deconstruction, transport, waste processing, and disposal. When an assessment of embodied carbon includes stages A, B, and C, this is a cradle-to-grave system boundary. A cradle-to-cradle assessment is further extended to include stage D, which quantifies potential impacts beyond the system boundary.

Operational Carbon
The global warming potential generated from mechanical, electrical, and plumbing needs during a building's use is perhaps most appropriately called operational carbon.

A building can have significant emissions in both categories of embodied carbon and operational carbon. The Royal Institute of British Architects (RIBA) and others advocate for the term and reduction of "whole life carbon," which is the combined value of embodied and operational carbon (RIBA, 2018).

Whole Building Life Cycle Assessment Standards

The International Organization for Standardization (ISO) as well as the **European Committee for Standardization** (CEN) both have sets of standard documents defining the environmental assessment process for construction materials and buildings. ISO is an international source for terminology and standards; the CEN documents are a harmonized European standard that references the ISO framework. North America does not have their own sustainability standard set, so CEN standards are often referenced in North American WBLCAs. Specific standards for WBLCAs include CEN's EN 15978: Sustainability of construction works — Assessment of environmental performance of buildings — Calculation method and ISO 21931-1, Sustainability in building construction — Core rules for environmental performance of construction works — Part 1: Buildings. The ISO standard is internationally recognized and is referenced by EN 15978. The EN 15978 standard is a part of the CEN's suite of standards for assessing the environmental performance of a building (CEN, 2011). Both the ISO and EN standard define terminology and requirements for performing a WBLCA.

__European Committee for Standardization__ (CEN, French: Comité Européen de Normalisation) is an association of standardization bodies from 34 European countries. The organization develops voluntary European standards (CEN, 2019).

Whole Building Life Cycle Assessment Calculators

Several software programs are capable of producing whole building life cycle assessments. Tally is a software application that takes material quantities from an **Autodesk Revit** digital building model and uses that information to produce life cycle assessments for buildings (KT Innovations, 2016). Tally was developed in 2008 by KT Innovations (a division of the architecture firm KieranTimberlake) in collaboration with thinkstep and Autodesk. Tally data comes from a custom **GaBi** database, which is intended to be specific to the United States (KT Innovations, 2016).

__Autodesk Revit__ is a building information modeling (BIM) software used by many architecture firms to produce digital building models for client presentation and construction documentation.

__GaBi__ is an externally-reviewed life cycle inventory database owned by thinkstep (thinkstep AG, 2016).

Athena Impact Estimator for Buildings (Athena IE) is a free software program from the non-profit organization Athena Sustainable Materials Institute (ASMI). It produces whole (or partial) building life cycle assessments from an input of building assemblies or a bill of materials (ASMI, 2016, p. 2). The life cycle inventory data comes from the proprietary Athena LCI database, the US LCI database, and the Ecoinvent LCI database v3.3 (ASMI, 2016, p. 25). Athena's database is regionally sensitive with regard to manufacturing technology, transportation, electricity grid, and recycled content differences for products produced in various regions (ASMI, 2016, p. 25).

Other life cycle assessment softwares for the building industry exist, such as LEGEP, One Click LCA, and **SOM**'s free Environmental Analysis tool; many are intended for use in specific countries or regions around the world (deWolf, 2017, p. 36). Because different software tools use different data sources and variables, WBLCAs are highly dependent on the software tool, the functional unit, system boundaries, and reference service life. A study comparing Tally and Athena's assessment results on the same building assembly revealed up to a 42% variance between Tally and Athena IE's calculated global warming potential (Schultz, Ku, Gindlesparger, & Doerfler, 2016).

*Skidmore, Owings & Merrill LLP (**SOM**) is an American architectural, urban planning, and engineering firm.*

A 2013 study of the environmental impacts of nine different structural systems compared three different life cycle assessment softwares - Tally, Athena IE, and SOM's Environmental Analysis Tool. For a heavy timber framed structure with plywood shear walls, Tally's global warming potential value was approximately 40-50% higher than Athena IE's (Stringer & Comber, 2015). They also tested several versions of Athena IE, and found notable differences in global warming potential between versions (p. 8). Athena IE showed greater carbon sequestration benefit in wood systems than Tally or SOM's Environmental Analysis Tool (p. 9).

Benchmarking & Comparing WBLCAs

There have been several efforts to benchmark the embodied carbon or environmental impacts of buildings (ASMI, 2017; deWolf, 2017, p. 5). DeWolf, an MIT phD student, created a database of embodied carbon of various buildings (deWolf, 2017). From the data, she reaches the following conclusions:

1) The embodied carbon of "typical buildings" ranges between 200 and 550 kg CO_2eq/m^2 on average.

2) Highly efficient buildings can reach embodied carbon values as low as 30 kg CO_2eq/m^2.

Each building's embodied carbon was strongly influenced by many variables such as structural systems, height, and size (deWolf, 2017). Another effort benchmarking effort, the Embodied Carbon Benchmark Study, spearheaded by the **Carbon Leadership Forum** at the University of Washington, established a database of the embodied carbon of over 1,000 buildings (Simonen, Rodriguez, Barrera, Huang, McDade, & Strain, 2017). The collected data suggests the following

*The **Carbon Leadership Forum** is an industry-academic collaboration aimed at reducing the embodied carbon in building materials* findings about the initial embodied carbon (cradle-to-construction site) of a building's structure, foundation, and enclosure:

1) For any building, this embodied carbon generally does not exceed 1,000 kg CO_2eq / m^2.

2) For a low rise (less than seven stories) residential building, the initial embodied carbon generally does not exceed 500 kg CO_2eq / m^2.

3) For commercial office buildings, initial embodied carbon ranges between 200 and 500 CO_2eq / m^2. for 50% of buildings in the database.

The report cautions that the database may not be a representative sample of current building practices — buildings that undergo environmental assessment may prioritize environmental performance. Furthermore, WBLCA analysis methods vary between studies, inhibiting alignment between examples. Several authors have noted the need for greater standardization in order to compare and benchmark WBLCAs (Miller, Gregory, and Kirchain, 2016; Moncaster et al., 2019).

WBLCAs, Embodied Carbon, and Regulations

Within the United States, **USGBC**'s LEED v4, the Living Building Challenge (LBC), **calGreen**, and other programs all include WBLCAs as a way to achieve a credit or level of environmental performance within a building certification system (Davies, Johnson, Doepker, Hedlund, 2018). The **LEED** credit requires a percentage reduction in environmental impacts for the proposed building compared to a baseline building. For the Living Building Challenge, the project must offset total embodied carbon (tons CO_2 eq) impact from its construction through a one-time carbon offset from an approved carbon offset provider (Living Building Challenge, 2014).

As of 2018, over 105 environmental sustainability certifications and regulations include reporting, but not necessarily reducing, the embodied carbon of buildings (Bionova Ltd., 2018). Austria, France, the Netherlands, and Norway all currently have government programs requiring or tying subsidies to the completion of whole building life cycle assessments (Bionova Ltd., 2018, p. 56).

*United States Green Building Council (**USGBC**) is a non-profit organization promoting sustainability for the built environment.*

***LEED** (Leadership in Environmental Design)*

***calGreen** is a mandatory state green building standards code for the state of California.*

WBLCA Limitations & Exclusions

The use stage (B1 through B7) of a building's life is difficult to estimate, as repairs are not generally anticipated, and normal maintenance such as painting may not have a set schedule. Thus, this stage is often not calculated in a WBLCA, even if the end-of-life stage is calculated.

While the primary building materials are input in most WBLCAS, some materials are usually omitted: sitework, wood used for concrete formwork, connections, and finishes. Additional environmental land impacts are difficult to quantify: from land disturbance, ecosystem alteration and destruction of vegetation (ASMI, 2016).

WBLCAs also currently omit mechanical, electrical, or plumbing (MEP) equipment. There is a lack of life cycle inventory data for these items; ASMI specifically mentions that they do not have the capabilities to calculate these impacts (ASMI, 2016). Some studies have attempted to quantify these omitted impacts. A 2018 recent study from the Carbon Leadership Forum at the University of Washington estimated the environmental impacts of MEP equipment in commercial office buildings in the Pacific Northwest (PNW) region. They found that the GWP of MEP systems of typical commercial office buildings in the Pacific Northwest region of the United States ranges from 41.2 to 66.3 kg CO_2 eq/m^2 for standard performance buildings and 53.6 to 74.8 kg CO_2 eq/m^2 for high performance buildings across sixteen model typologies (Rodriguez, Lee, Simonen, & Huang, 2018). HVAC systems were found to contribute the highest percentage to environmental impacts, followed by electrical and plumbing systems (Rodriguez et al., 2018).

The common software tools for WBLCA (Tally and Athena IE) employ a process LCA approach. A process LCA collects emissions and/or energy data for specific processes in order to calculate the life cycle impacts of a product or system (Seo & Foliente, 2016, p. 25). This approach has a high level of specificity, and many standards like EN 15978 and ISO 21930 recommend the use of this approach for WBLCA (Seo & Foliente, 2016, p. 25). The process approach is not the only LCA approach; input-output and hybrid LCA are two other approaches, with the hybrid approach combining aspects of process and input-output approaches (Lenzen & Trolar, 2002). An input-output analysis takes an expanded view of the environmental impacts of a product or system. The input-output method estimates impacts by using monetary transaction data to approximate the emissions intensity of industry sectors (Seo & Foliente, 2016, p. 25). Process-based life cycle assessments must define specific boundaries for their assessments and have been found to presumably under-estimate environmental impacts by 50% compared to input-output methods (Lenzen & Treloar, 2002). In a reassessment of a WBLCA by Borjesson and Gustavsson (2000), Lenzen & Treloar found that the process-based approach underestimated the environmental impacts of the multi story building (in timber and concrete) by a factor of about two (Lenzen & Treloar, 2002, p. 1). The following case studies are constrained to the process approach used by the WBLCA softwares Tally and Athena IE.

Review of Existing WBLCAs of CLT Buildings

Life cycle assessment comparisons of CLT buildings suggest that CLT buildings have lower environmental impacts (including global warming potential) than functionally equivalent concrete or steel buildings. Many comparisons have been carried out in order to achieve a credit for the Leadership in Energy and Environmental Design (LEED) building certification program. In LEED V4, the WBLCA **credit** specifies that "for new construction, conduct a cradle-to-grave life-cycle assessment of the project's structure and enclosure that demonstrates a minimum of 10% reduction, compared with a baseline building, in at least three of the six impact categories, one of which must be global warming potential. No impact category assessed as part of the life-cycle assessment may increase by more than 5% compared with the baseline" (USGBC, 2013).

*The LEED **credit** is entitled is "Building Life-Cycle Impact Reduction, Option 4-Whole Building Life Cycle Assessment (LCA)," and it falls under the within the Materials and Resources category in LEED V4.*

However, LEED's 10% credit requirement may not be a good measure for comparisons. WBLCA comparisons should be viewed with a generous margin of error, due to the numerous embedded assumptions and uncertainties. ASMI, the company behind the Athena IE software, states that their results should be viewed with an assumption of at least a 15% margin of error — WBLCA comparisons with a less than 15% difference are presumed to be insignificant (ASMI, 2016). ASMI notes that uncertainties probably have balancing effects on the results but nevertheless should not be seen as definitive (ASMI, 2016).

Several whole building life cycle assessments of buildings with CLT materials have been completed using the Athena Impact Estimator (Court, Podesto, & Harburg-Petrich, 2013; Grann, 2014; Robertson, Lam & Cole, 2012; Teshnizi, Pilon, Storey, Lopez, & Froese, 2018).

SOM (2013) uses their free Environmental Analysis Tool software and Hafner & Schafer use LEGEP (2018). Darby, Elmualim, & Kelly do not use any specific software but compile data from several sources (2012). Short summaries of several of these WBLCAs are provided on the following pages.

5-story office building, Los Angeles, USA (2013)

The Structural Engineers Association of California compare eight structural & seismic systems (two concrete, two masonry, two steel, and two timber systems) for a prototype 5-story office building in Los Angeles with Athena IE v.4.02 (Court, Podesto, & Harburg-Petrich, 2013). In general, the relative environmental impacts of the timber structural systems are lower than the steel buildings, and the impacts of the steel buildings are lower than the concrete and masonry. The light timber building has the lowest GWP (4.9 kg CO_2 eq./ft^2), and the heavy timber building has a slightly higher GWP (7.4 kg CO_2 eq./ft^2). The concrete, steel, and masonry structural systems have GWPs that range from 14.5 kgCO_2 eq./ft^2 to 21 kg CO_2eq./ft^2. The only environmental impact where the mass (heavy) timber structural systems has worse environmental impacts is eutrophication. Data source for CLT is not stated.

Court, A. B., Podesto, L., & Harburg-Petrich, P. (2013). SEAOC LCA study comparing environmental impacts of structural systems. In *SEAOC 2013 Convention Proceedings* (pp. 137–153). Retrieved from https://www.seaoc.org/store/ViewProduct.aspx?ID=9630924

Bridport House, London, United Kingdom (2012)

Darby, Elmualim, & Kelly perform a cradle-to-grave WBLCA of the Bridport House in London, an eight story, 4,154 m^2, multi-family residential building (2012). The building has concrete foundations and a structure of CLT walls, floors, and roof panels at thicknesses between 97 mm and 223 mm. They compare the impacts of the CLT building with an equivalent reinforced concrete frame option, which has a concrete structure with lightweight steel stud interior walls. The concrete building has a heavier structure which requires larger foundations. The scope of materials assessed are the structural materials and any non-structural elements affected by the structure. They compare carbon sequestration scenarios for the CLT structure: adding 100%, 50%, or 0% of the sequestered carbon (and wood end-of-life) emissions to the embodied carbon. With 100% of sequestered carbon, the embodied carbon of the CLT frame is approximately 10 times lower than when 0% of the sequestered carbon is included (Darby, Elmualim, & Kelly, 2012, p. 6). At the end-of-life, for the embodied carbon of CLT panels, incineration with energy recovery

Darby, H., Elmualim, A., & Kelly, F. (2012). *A case study to investigate the life cycle carbon emissions and carbon storage capacity of a cross laminated timber, multi-storey residential building.* University of Reading.

resulted in a lower GWP than landfilling, assuming that 20% of the carbon in the wood is re-emitted and no landfill gas is recovered.

University of Massachusetts Amherst (2018)

Gu and Bergman (2018) use Athena IE (version 4B) to calculate the cradle-to-grave impacts of a university building at the University of Massachusetts in Amherst, Massachusetts, including operational energy and water use. The four-story, 87,500 ft^2, building's structure mixes glulam and structural steel framing with composite CLT floor panels topped with a layer of reinforced concrete. CLT wall panels and glulam cross-bracing provide lateral force resistance. When comparing the proposed building to a functionally equivalent design (containing "conventional" and light steel frame construction), they find a 13.1% reduction in global warming potential (Gu & Bergman, 2018, p. 5). This goal of this comparison was to demonstrate the reduction for the LEED V4 credit.

Gu, H., Bergman, R. (2018). *Life cycle assessment and environmental building declaration for the design building at the University of Massachusetts.* Gen. Tech. Rep. FPL-GTR-255. U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 1-73.

Brock Commons Tallwood House, University of British Columbia (2018)

A cradle-to-grave comparison of an eighteen story, 15,115 m^2, mass timber university building at the University of British Columbia in Vancouver, British Columbia, reveals that the CLT building has approximately 9% lower environmental impacts in five of six environmental impact categories than an equivalent concrete building, including a 25% lower GWP (Teshnizi, Pilon, Storey, Lopez, & Froese, 2018). The mass timber building utilizes concrete for the first and second floor slabs, foundations, and building cores. The floors are CLT, and parallel strand lumber and glulam columns support a steel roof deck. (Teshnizi et al., 2018, p. 174-175). This study counts the carbon storage of wood as a credit (negative) contribution to GWP.

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. *Proceedings of the 25th CIRP Life Cycle Engineering (LCE) Conference* (pp. 172–177). University of British Columbia. https://doi.org/10.1016/j.procir.2017.11.121

Wood Innovation Design Center, Prince George, BC (2014)

A WBLCA report for the Wood Innovation Design Center, a 4,785 m^2 (gross floor area) mixed-use building in Prince George, British Columbia compares a mass timber design with a baseline building, seeking to achieve a LEED v4 credit. The mass timber building's structure is glulam beams and columns with CLT floor and CLT walls at elevator and stairs core. The mass timber building, compared to the concrete and steel building, achieves at least a 10% reduction in

Grann, B. (2014). *Wood Innovation and Design Center whole building life cycle assessment*. Retrieved from FPI Innovations website: https://fpinnovations.ca/Extranet/Pages/AssetDetails.aspx?item=/Extranet/Assets/ResearchReportswp/3126.pdf#.W749RmhKjic five of the six environmental impact categories tracked by LEED V4 (Grann, 2014). The mass timber building has a 88% lower GWP than the concrete building, primarily due to the assumption that only 23% of the carbon in wood materials will decompose in the landfill and return to the atmosphere (Grann, 2014, p. 15). This study excludes the building's use stage (modules B1-B7) from the assessment.

Discovery Place - Building 12, Burnaby, BC, Canada

Robertson, Lam, & Cole compare WBLCA results for a 14,233 m^2 mass timber building (glulam columns/beams with CLT floors) with that of an equivalent reinforced concrete office building (2012). The scope of this life cycle assessment is cradle-to-construction site, with a functional unit of the structure and building enclosure. They find that the mass timber building has a lower environmental impact in 10 of 11 assessment categories. Most significantly, the timber building has a 71% lower GWP. The GWP of the timber building is 126 kg CO_2 eq./m^2 compared to 420 kg CO_2 eq./m^2 for the concrete building. The GWP includes carbon storage of wood as a credit (negative) contribution to GWP. The life cycle data for the CLT material comes from a pilot plant facility (Robertson, Lam, & Cole, 2012).

Robertson, A. B., Lam, F. C. F., & Cole, R. J. (2012). A Comparative cradle-to-gate life cycle assessment of mid-rise office building construction alternatives: laminated timber or reinforced concrete. *Buildings*, 2(4), 245–270. https://doi.org/10.3390/buildings2030245

Structural System Comparison, Trondheim, Norway

Hoping to demonstrate the climate change mitigation potential of wood structures, Skullestad, Bohne, & Lohne analyze a whole building life cycle comparison of a reinforced concrete versus a mass timber structural system for 3, 7, 12, and 21 story building versions of a hotel located in Trondheim, Norway (2016). The reinforced concrete building contains reinforced concrete foundations, columns, floor slabs, and structural shear walls. The mass timber building has concrete foundations with a glulam frame, CLT floors and CLT structural shear walls. The authors apply three calculation approaches with varying analysis perspectives, handling of biogenic CO_2 emissions, allocation rules, and accounting for recycling benefits. They find that if 90% of timber production residues and timber material waste is incinerated with heat recovery, replacing natural gas, then the timber structure has a negative global warming potential when considering the avoided impacts of natural gas extraction and combustion. Across all calculation approaches and scenarios, the timber structures result in lower global warming potentials than the reinforced concrete.

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

Limitations of Reviewed Case Studies

Of the reviewed whole building life cycle assessments for buildings with CLT, few mention the specific inclusion or exclusion of connections, sealants, or other finishes. Especially when comparing CLT structures to other structural systems, a partial assessment may overestimate the benefits of CLT buildings. WBLCAs of reinforced concrete buildings typically include the quantities of reinforcement steel rebar, which is the primary secondary material for that structure. For a fair comparison, WBLCAs with CLT should also include secondary materials of connections and finishes.

To interpret a WBLCA comparison of wood versus steel or concrete buildings, the data source and specifications of the primary materials need to be stated. For WBLCA comparisons with CLT, studies often use lumber data in place of CLT or do not state their data source. For the steel components of WBLCAs, the recycled content of the steel (and source country) dramatically alters steel's environmental impacts. For concrete, the mix design, percentage of fly ash, carbonation, and end-of-life recycling are key variables that affect the environmental impacts.

Another consideration for WBLCA comparisons of wood versus concrete is the avoided use of forest resources in the concrete scenario. Those trees could instead continue growing and absorbing carbon in the forest, or the trees could be harvested for bioenergy use. None of the studies noted above consider this avoided carbon. However, a WBLCA study of wood frame versus concrete buildings by Borjesson and Gustavsson analyzed those two scenarios, along with several other variables (2000). In many scenarios, they found that the wood frame buildings could have a lower GWP than the concrete. However, in some cases, the wood frame could have a larger GWP than the concrete (p. 587). This occurred when the buildings had shorter life spans and when the end-of-life scenario for wood frames was landfilling without landfill gas collection.

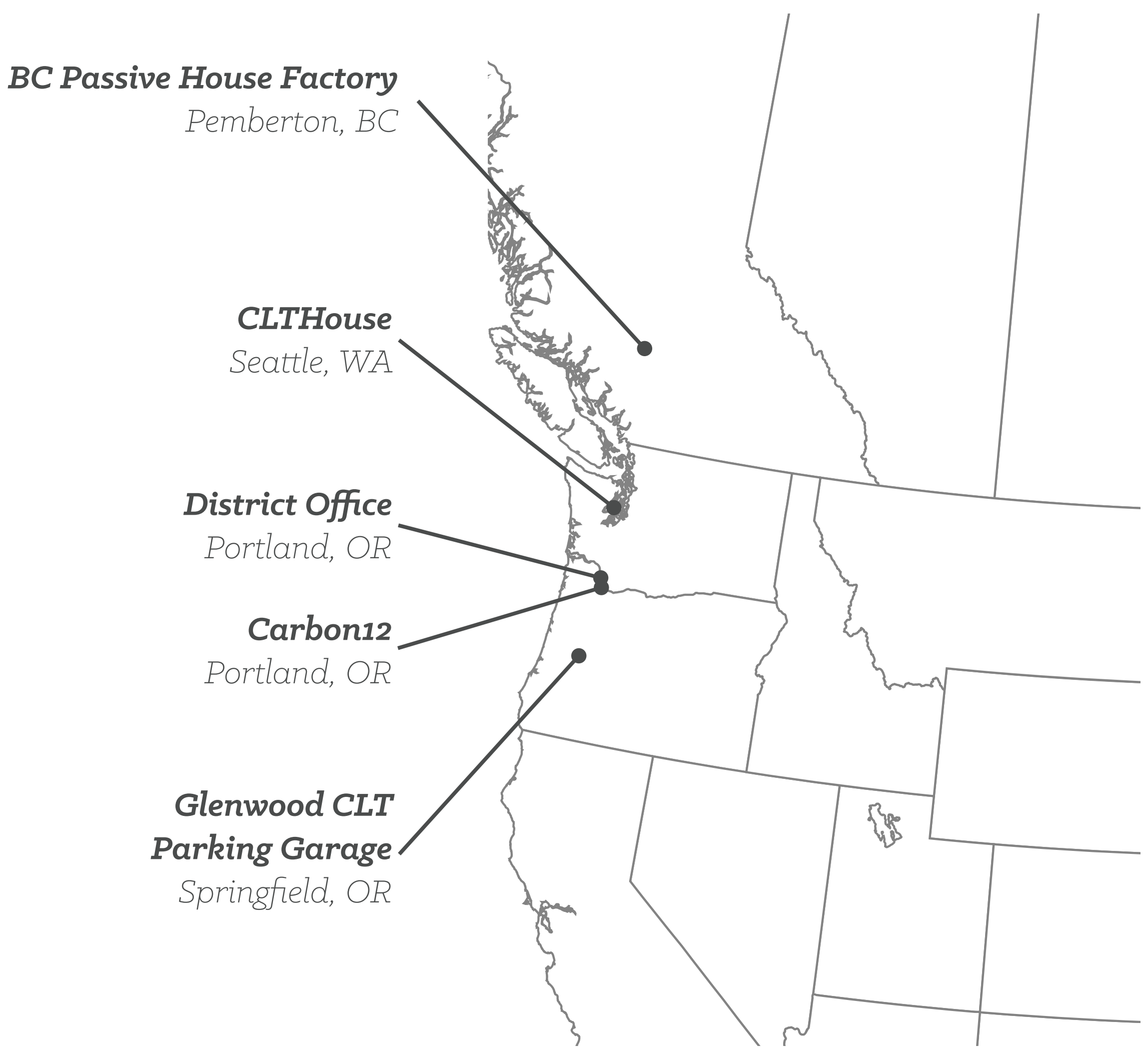


Figure 5 CLT Case Study Project Locations

CLT WBLCA CASE STUDY BACKGROUND

For this case study series, five projects using CLT for some or all of their structure were selected for WBLCAs. The projects range in building type and scale: two mixed use buildings, one single-family residential, a industrial building, and a parking garage. Although the authors would have preferred a wider geographical range, the projects are concentrated in the Pacific Northwest region, which is reflective of where CLT construction is concentrated in the United States and Canada. Three projects are located in Oregon, one in Seattle (Washington), and one in Canada. Different calculators (Tally and Athena IE) and calculation methods generate six WBLCAs for each project. This introduction for the case study series gives reviews existing WBLCAs of CLT buildings and discusses methodologies common to the case studies.

General Methodology for CLT Case Study Series

For each case study, the software program Tally and the software program Athena IE generate multiple whole building life cycle assessment (WBLCA) reports for a reference building. Tally, the Autodesk Revit add-in, links material quantities from a Revit model to a database of material environmental impacts. Tally users assign a Tally-specific material to each Revit material usage. After all the materials are assigned, additional information about the building is entered into the Tally program, such as location and area. Tally then exports a formatted WBLCA report in pdf and Excel.

For the Athena IE WBLCA reports, a new project is created with background information about the building type and location. Within the project, building assemblies are added with their respective material compositions. For these case studies, the generic assembly “project extra materials” is used to enter the building’s materials in Athena IE. Tally materials are matched to their closest equivalent in Athena IE, and their quantities are entered into Athena IE through measures of mass, area, or volume. Although Tally's reports only provide the calculated mass of each material, the volume and area can be manually calculated using the density shown within the Tally software. When all the materials are added, Athena IE can generate a report of environmental impacts as well as a bill of materials. The bill of materials displays the mass of the materials, which allows for validation of Athena IE and Tally inputs. Athena IE does slightly increase material quantities via construction waste factors, which cannot be manually changed, so Athena may have slightly higher mass calculations in many cases. However, in other cases, entering Tally's material volume into Athena results in a slightly lower material mass than Tally's value — presumably due to different material density assumptions.

Tally and Athena IE's material calculation differences as well as other differences between the software (methodology and database sources) produce varying WBLCA results. In some cases, Tally may result in larger calculated impacts, while in other cases, Athena IE may result in larger calculated impacts. For each case study, to see the range of results, Tally and Athena IE's WBLCA data values are united in new excel graphs for the impact categories of global warming potential, acidification potential, eutrophication potential, smog formation potential, and primary energy demand.

Functional Unit for CLT Case Study Series

The functional unit for these case studies is the gross m^2 of conditioned built space, unless noted otherwise.

Reference Study Period for CLT Case Study Series

Many WBLCAs use a reference study period and reference service life of 50 years, but this case study series selects a reference service life of 75 years. LEED v4 Reference Guide for BD+C (USGBC, 2013) recommends using a service life of 60 years, at a minimum. Other WBLCA standards require a service life of 75 years. ASTM E921 requires a minimum service life of 75 years, and ASHRAE 189.1 suggest that the design life of most building types should be 75 years (Yang, 2018). Extending the service life of a building is a resilient, sustainable strategy to reduce the overall embodied energy and carbon of a building (International Energy Agency, 2016, p. 54, 74).

Impact Categories for CLT Case Study Series

Although both softwares report the impact category of ozone depletion potential, these results are excluded from the case studies due to statistical insignificance. For all case studies, the total value of ozone depletion potential is less than 1 kg CFC^{-11} eq. Known ozone depleting substances (primarily **CFCs and HCFCs**) are regulated through the Montreal Protocol, first signed in 1987. CFCs have been completely phased out of legal production, and HCFCs are being phased out by 2020 in developed countries and 2030 in developing countries (United Nations Environment Program, 2019). Thanks to this effective legislation, the ozone layer has remarkably regenerated and is expected to fully recover by 2050 (United Nations Environment Program, 2019).

CFCs *(chlorofluorocarbons) and* ***HCFCs*** *(hydrochloro-fluorocarbons) are gases formerly used for aerosol sprays, refrigeration, air-conditioning and foam applications (United Nations Environment Program, 2019).*

Software Assumptions for CLT Case Study Series

The following subsections detail the inherent assumptions of Tally and Athena IE, which are used in this case study series. Some of this software information is not readily available and was requested via email communication with the software companies.

Software Versions and Databases - Tally

These case studies employ Tally's non-commercial (educational) version 2018.09.27.01, which is identical to the commercial version. The 2018 Tally version carries out the LCA in GaBi 8.5 using the GaBi 2018 database and modeling principles. For end-of-life scenarios, Tally consults the US EPA's **WARM** construction and demolition rates and methods, as well as industry sources. Tally reports impacts according to the TRACI 2.1 environmental impact categories.

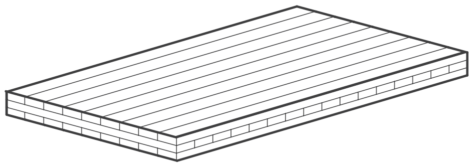
EPA ***(Environmental Protection Agency)***

EPA's ***WARM (Waste Reduction Model)*** *is a software for tracking and reporting greenhouse gas (GHG) emissions, energy consumption, and economic impacts from different waste management practices.*

Software Versions and Databases - Athena IE

The first three case studies (District Office, Carbon 12, and the Glenwood CLT Parking Garage) use Athena version 5.3, while the last two case studies (CLTHouse and BC Passive House Factory) use Athena IE version 5.4, which was released during the study period. The software is based on regional information for electricity grids, transportation, and product manufacturing technologies (ASMI, 2016, p. 24). The city was selected for each case study in this series, theoretically signaling regional settings for electricity mix, production practices, transportation distances, and average distance to landfill. Athena IE reports environmental impacts for the impact categories set out in TRACI 2.1.

CLT



CLT and Wood Assumptions - Tally

Tally's software offers three product material choice options for CLT. One option is a generic CLT, another option is for 57 mm thick CLT from the manufacturer **KLH**, and the final option is for 320 mm thick CLT from the manufacturer KLH. Tally's data source for generic CLT comes from averaged North American glulam life cycle data, which is adjusted to reflect the differences in density between CLT and glulam (personal communication with Roderick Bates at Tally, via email, October 25, 2018).

__KLH__ is a CLT manufacturer with a central factory located in Austria. They were one of the first manufacturers of CLT, and their CLT is in use globally.

Tally CLT Density Assumptions:

KLH - 320 mm thick CLT: 480.1875 kg/m^3
KLH - 57 mm thick CLT: 484.7368 kg/m^3
Generic CLT - 490 kg/m^3

Within Tally, the CLT can be specified to have no finish or one of five finish options can be manually added the to CLT material in the program: interior acrylic paint, exterior acrylic paint, water-based wood stain, **Brillux** acrylic-based façade paint, and Brillux silicone-based façade paint. For the paint options, the number of coats over primer can be specified. For the water-based wood stain, the coverage rate can be specified

__Brillux__ is a European paint and construction materials company.

Including and Excluding Biogenic Carbon

Tally's most recent version, released in 2018, offers the option to include or exclude **biogenic carbon** from calculations. Trees and other plants (biomass) absorb CO_2 through the process of photosynthesis, incorporating it into plant tissue as carbon (C). This biogenic carbon is emitted as CO_2 and/or CH_4 (biogenic methane) when trees (or other biomass fuels) are combusted or decay. The production of wood construction materials emits biogenic carbon if wood waste is combusted for energy for manufacturing, or if leftover harvest residues are combusted. Wood products also emit biogenic carbon when they decompose in a landfill or are burned for energy at the end of a product's life. Tally's option to include or exclude biogenic carbon is at the project level; one cannot specify to include or exclude it for an individual material.

__Biogenic carbon__ is "carbon derived from or contained in biomass." Biomass is "material of biological origin excluding material embedded in geological formations and material transformed to fossilized material" (ISO, 2018, p. 10).

When Tally ***includes*** biogenic carbon, the carbon content of wood materials enters the LCA system during manufacturing as a negative credit against the GWP. During the end of life, when the wood leaves the system, the emitted CO_2 is counted as part of the GWP. The wood's carbon content that does not decay in the landfill remains a negative credit against GWP. In Module D, burning wood or capturing landfill gas for energy results in a negative credit to GWP for avoided fossil fuel use. Avoided fossil fuel use is based on the United States national average electricity grid carbon intensity and is not locally sensitive. For more information on Tally's biogenic carbon options, see Appendix 1.

When Tally ***excludes*** biogenic carbon, the carbon content entering and leaving the product system is excluded — thus there is no negative credit to GWP for carbon content. This approach is more conservative than including biogenic carbon. However, any emissions of biogenic methane (CH4) from biogenic sources are still included. In Module D, burning wood or capturing landfill gas for energy still results in a negative credit to GWP for avoided fossil fuel use. For more information on Tally's biogenic carbon options, see Appendix 1.

Wood end-of-life

Disposal of CLT and all wood materials is calculated based on the average percentages sent to each scenario: for Tally, 14.5% is assumed to be recovered (recycled), 22% is assumed to be incinerated with energy recovery, and 63.5% is assumed to be landfilled (personal communication with thinkstep, Tally's LCA partner, via email, May 16, 2019).

For the landfilled portion, 50% of wood is assumed to decompose into landfill gas, 80% of which is recovered. Of the recovered landfill gas, 31% is **flared**, 36% is released as an emission to air, and the remainder is used for energy recovery (personal communication with thinkstep, Tally's LCA partner, via email, May 16, 2019). 50% of the wood does not compose, meaning that 31.75% of the carbon from the original discarded CLT panel is permanently stored (see figure 5).

Flaring *landfill gas is the process of burning landfill gas as a flame. This combustion process takes* CH_4 *(methane) gas and emits it as* CO_2*, a much less potent greenhouse gas (USEPA, 2006).*

END-OF-LIFE CLT ASSUMPTIONS

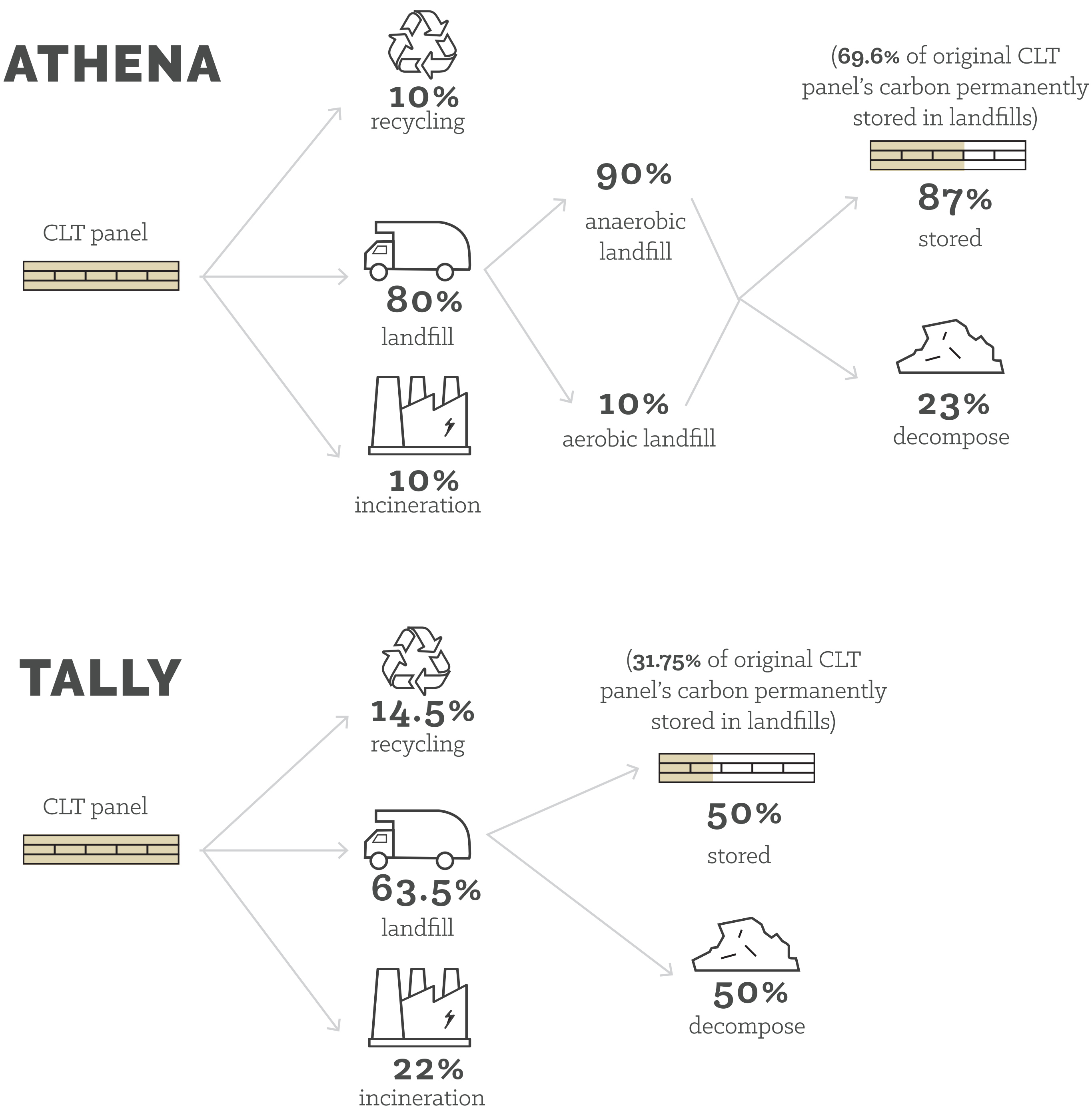


Figure 5 End of Life CLT Assumptions

CLT and Wood Assumptions - Athena

ASMI's data for CLT's environmental impacts comes from a 2013 aggregate LCA study of Canadian CLT manufacturers (personal communication with ASMI via email, April 25, 2019). Athena does not have any other CLT options in the program.

Biogenic Carbon

Athena IE accounts for the carbon stored in CLT and wood as a negative emission (GWP credit) when it enters the product life cycle. At the end of the wood product's life, biogenic carbon emissions are added to GWP just like other greenhouse gas emissions (ASMI, 2016, p. 32). Biogenic carbon emissions during manufacturing are not included in global warming potential (personal communication with ASMI via email, July 12 2019). This accounting method is based on reference standards **PAS 2050**, ISO/TC 14067, and WRI GHG Protocol for Products which require no land use change for this method (ASMI, 2016). However, presumably, if land use change did occur, Athena IE's biogenic carbon procedure would no longer be valid. In Athena IE, biogenic carbon cannot be excluded as in the Tally software.

Publicly Available Specification (PAS) *2050 is a standard for the assessment of the life cycle greenhouse gas emissions of goods and service, developed by the British Standards Institution in 2008.*

Wood End-of-life

Disposal of wood products divides into the average percentages sent to each scenario: 10% is assumed to be recycled, 10% is assumed to be incinerated with energy recovery, and 80% is assumed to be landfilled (ASMI, 2016, p. 34). This scenario mix comes from the National Council for Air and Stream Improvement (NCASI) Carbon Storage Tool. For the percentage of wood products that are landfilled, 90% is sent to anaerobic landfills and 10% is sent to aerobic landfills. For the 90% in anaerobic landfills, 23% of wood decomposes into 50% methane and 50% carbon dioxide (although 10% of that methane is assumed to oxidize to carbon dioxide before reaching the landfill surface). It is assumed that 82% of the anaerobic landfills have landfill gas capture systems with a 90% gas capture efficiency. For the 10% sent to aerobic landfills, 23% of the wood decomposes into 100% carbon dioxide. Overall, 69.6% of the carbon from the original discarded CLT panel is permanently stored in the landfill (refer to figure 5).

CONCRETE

Concrete consists of approximately 41% gravel, 25% sand, 18% water (reduced during curing), 6% air, and 7-15% cement depending on the concrete's performance requirements (**NRMCA**, 2008, p. 7). Producing concrete is energy-intensive; 90% of the greenhouse gas emissions are attributable to the production of cement for concrete (Webster et al., 2012, p. 19). Within the cement manufacturing process, approximately 40% of carbon emissions result form the burning of fossil fuels to heat the kiln, and the remaining 60% comes from the breakdown of limestone in a chemical reaction that occurs during processing called **calcination** (Webster et al., 2012, p. 19).

NRMCA *stands for National Ready-Mix Concrete Association.*

Calcination *occurs when limestone (calcium carbonate)is heated and broken down to calcium oxide, releasing* CO_2*.*

The primary heating methods for cement production in the United States are wet, long dry, dry with preheater and dry with preheater and precalciner. The energy and emissions vary between methods; the preheater and precalciner kilns use 85% less thermal energy than wet kilns on average (Webster et al., 2012, p. 20). Industrial byproducts called **supplementary cementitious materials** (SCM) can supplement a portion of the cement, improving concrete's strength and reducing CO_2 emissions (NRMCA, 2008, p. 10). The aggregate in concrete can be natural or mechanically crushed gravel. Per ton, naturally occurring gravel requires approximately 20 MJ oil and 9 MJ electricity, whereas mechanically crushed gravel requires 120 MJ oil and 50 MJ electricity (Gustavsson & Sathre, 2006). However, the extraction of natural gravel may be damaging to sensitive habitats such as river banks (American Society of Civil Engineers, 2010, p. 151).

Several common ***supplementary cementitious material****s are fly ash (a byproduct of the coal industry), blast furnace slag and silica fume.*

After curing, concrete can absorb CO_2 from the environment through a process called **carbonation** (also called carbonization). The carbonation process occurs when air and water penetrate the concrete, and the overall rate of carbonation is affected by humidity, temperature, porosity, and the concrete mix (Stripple, Ljungkrantz, Gustafsson, & Andersson, 2018).

During ***carbonation*** *of concrete,* CO_2 *binds to the calcium in the lime in the hardened concrete.*

Carbonation rates will vary based on concrete's use and life cycle stage. A concrete wall covered with cladding materials will experience limited carbonation compared to concrete ground into gravel (Borjesson & Gustavsson, 2010, p. 578). If concrete is recycled to road base or gravel, it will likely experience much more carbonation than aggregate embedded in new concrete (Stripple et al., 2018). Compared to the CO_2 emissions from calcination, the lifetime CO_2 sequestration from carbonation in a concrete structure may be as low as 11%, when a 20 year life span without recycling is considered (Possan, Felix, & Thomaz, 2016). Another estimate places the upper limit of carbonation (as a percentage of CO_2 originally emitted in calcination) at 57% for a 100 year life span, when ideal recycling practices exist (Pade & Guimaraes, 2007).

Concrete recycling practices are not well-documented in the United States, but the overall percentage of concrete recycled was estimated to be 82% in the United States in 2005 by the Construction Materials Recycling Association (World Business Council for Sustainable Development, 2009).

Concrete Assumptions - Tally

Carbonation in concrete is not included (personal communication with Roderick Bates at Tally, via email, May 28, 2019). Concrete data comes from life cycle data in **NRMCA's** industry-wide EPD. Quantities of steel rebar reinforcement may be specified as low, moderate, or high for the intended concrete application (i.e. foundation, column, footing). Alternatively, quantities of steel rebar may be specified as the average mass per cubic meter.

Concrete end-of-life

55% of concrete is assumed to be recycled, and 45% of concrete is landfilled. Module D credits GWP for the avoided emissions from virgin concrete production, but accounts for the emissions from grinding concrete aggregate in preparation for the production of new concrete (information provided in Tally output reports, 2018-2019).

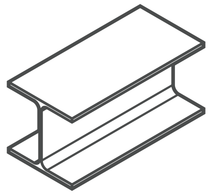
Concrete Assumptions - Athena

Within Athena, a custom concrete mix can be specified. For this case study series, standard concrete mixes were used. Athena IE does not include carbonation from concrete (personal communication with ASMI via email, April 24, 2019). Concrete data comes from life cycle data published by NRMCA (ASMI, 2016). Quantities of steel rebar reinforcement are automatically calculated based on concrete application and necessary strength. Quantities of steel rebar reinforcement must be separately calculated by the user if concrete is added as an extra material.

Concrete end-of-life

Athena IE assumes all concrete goes to a landfill at end-of-life, incurring a small amount of environmental impact from transport to the landfill and demolition (personal communication with ASMI via email, April 26, 2019). None of the concrete is recycled.

STEEL



Steel Assumptions - Tally

Tally's life cycle inventory comes from World Steel reports, which specify recycled percentages and production methods for steel material types. The furnace type and recycled content significantly affect steel's environmental impacts. Structural steel can either be produced in an electric-arc furnace (EAF) or in a less efficient basic oxygen furnace (BOF) powered by coal or natural gas. EAF steel has a 93% average recycled (secondary) steel content, whereas BOF steel can only have a 25% average recycled (secondary) steel content (**AISC**, 2017). All hot-rolled shapes produced in the United States are produced using electric-arc furnaces; the EAF production method results in this steel having an average recycled content of 93% or more (AISC, 2018a). A common cold formed structural steel, hollow structural section (HSS), may be produced in either BOFs or EAFs. For HSS production in the United States the average recycled content is 90% if produced in EAFs but only 30% if produced in BOFs (AISC, 2018a).

__AISC__ is the American Institute of Steel Construction, a non-partisan, non-profit technical institute and steel trade association.

Tally's steel recycled content assumptions are listed below:

1) Hot rolled structural steel - 100% recycled content
2) Cold formed structural steel - 16% recycled content
3) Steel rebar for concrete reinforcement - 16.4% recycled content
4) Galvanized steel - 44% recycled content

Steel end-of-life

Most steel and metals can have high rates of recycling when a building is eventually demolished or dismantled. Steel is a desirable material for recycling; there are high recovery rates because the magnetic properties aid in easy removal from waste streams (World Steel Association, 2019).

Tally's steel end-of-life assumptions for steel are listed below:

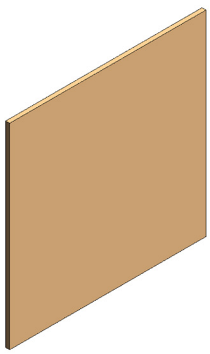
1) Hot rolled structural steel - 98% recycled (2% landfilled)
2) Cold formed structural steel - 98% recycled (2% landfilled)
3) Steel rebar for concrete reinforcement - 70% recycled (30% landfilled)
4) Galvanized steel - 98% recycled (2% landfilled)

Steel Assumptions - Athena IE

Like Tally, Athena's steel information comes from World Steel (personal communication with ASMI via email, April 26, 2019). Because World Steel reports specify recycled content values, theoretically Athena IE and Tally use the same steel recycled content values. However, Athena IE, where possible, treats all offshore products as if they were manufactured in North America, because of the lack of consistent and reliable international data (ASMI, 2016, p. 24). Steel produced in North America is more likely to be produced with an electric arc furnace (EAF), which emits about half the CO_2 emissions of BOFs (Webster, et al., 2012, p. 30). Additionally, the countries that primarily use BOFs often have fossil fuel intensive electricity sources, compounding the emissions from the process itself. For example, the greenhouse gas emissions of a hot-rolled structural steel section from China are three times larger than one produced in the United States (AISC, 2018b). Thus, if the building's steel comes from China, WBLCA impacts calculated with North American methods will underestimate the steel impacts. As of 2017 21% of the structural steel used in the U.S. was imported from overseas (AISC, 2018a, p. 3).

The larger impacts of steel produced in China is due to the furnace type as well as China's electricity mix, which is heavily coal-powered (AISC, 2018b).

CASE STUDY: CLT WALL



8.9 cm thick x 5m x 5m CLT wall segment used for GWP comparison

In order to understand CLT's environmental impacts separately from the WBLCA case studies, an LCA of embodied carbon (global warming potential) and embodied energy (primary energy demand) for a single wall element is carried out in Athena and Tally.

The compared object is a single 5 m long x 5 m high x 8.9 cm thick CLT wall. Athena's only CLT option and both of Tally's CLT options are tested — a generic CLT option (based on adjusted glulam LCI information) and a CLT option from the Austrian manufacturer KLH. Additionally, two Tally options are calculated including and excluding biogenic carbon. Finally, the results are separated by life cycle modules: one chart shows impacts from life cycle modules A and C, and the other shows impacts from life cycle modules A, C, and **D** (recycle, reuse, and recovery benefits beyond the system boundary).

The highest GWP is 1835 kg CO_2 eq for the KLH CLT wall calculated in Tally, excluding biogenic carbon, and excluding module D benefits beyond the system boundary. The lowest GWP is -546 kg CO_2 eq for Athena's CLT wall, excluding module D. The highest GWP is approximately five times larger than the smallest.

Including biogenic carbon, Tally's results generally show an overall negative GWP, because some carbon remains permanently stored in the portion of the wood that is assumed to be landfilled. The only case where including biogenic carbon does not result in a negative

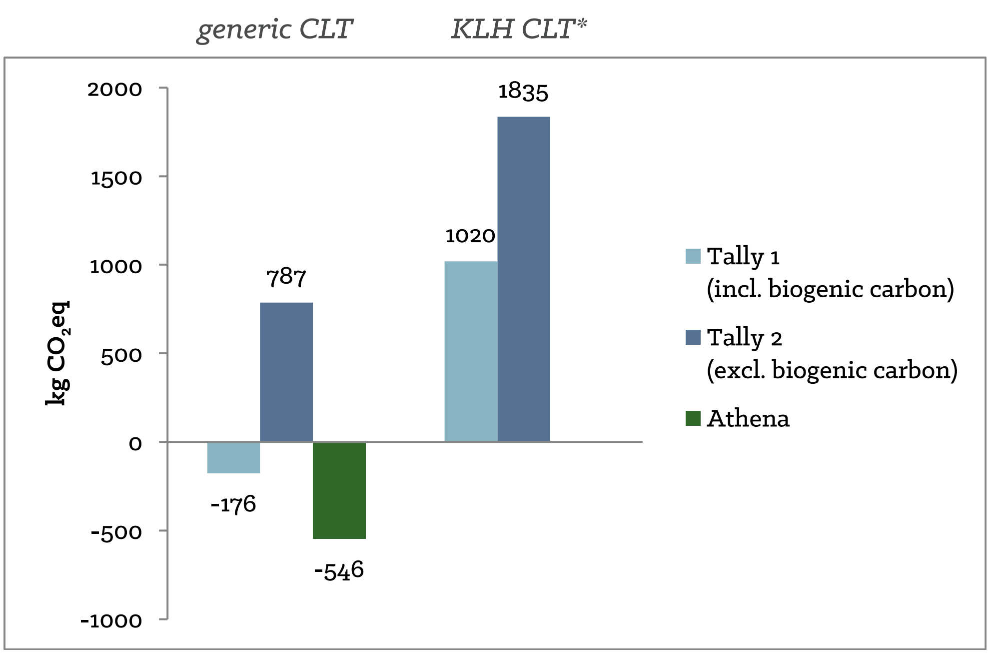
Module D *considers benefits beyond the system boundary, at the end of the building's life such as the potential avoided fossil fuel emissions from burning wood or from recycling materials. According to the Tally report, module D for CLT credits recovered wood products as an avoided burden.*

CLT GWP is for KLH CLT that excludes module D benefits beyond the system boundary.

The inclusion of module D reduces GWP for Tally 1 (including biogenic carbon) for both generic and KLH CLT, and module D reduces GWP for KLH CLT when excluding biogenic carbon. However, the inclusion of module D increases GWP for generic CLT in Tally 2 (excluding biogenic carbon) and increases GWP substantially for Athena, shifting GWP from negative to positive.

Primary energy demand varied between softwares and system boundaries but not between the inclusion or exclusion of biogenic carbon. Within Tally, the software boundary including module D decreased the primary energy demand, but module D did not significantly decrease Athena's primary energy demand. For the KLH CLT material, including module D decreased the primary energy demand by more than half.

This example reinforces the importance of transparent reporting of biogenic carbon assumptions and wood material data in whole building life cycle assessments, as well as an opportunity to standardize biogenic carbon material accounting methods across WBLCA softwares. Extrapolated across a whole building, the difference in estimates of CLT's global warming potential could shift the global warming potential of the entire building.



**KLH CLT is a manufacturer-specific CLT option only available in Tally, not Athena IE.*

Figure 6 GWP (kg CO_2 eq) of CLT wall: life cycle stages **A & C**

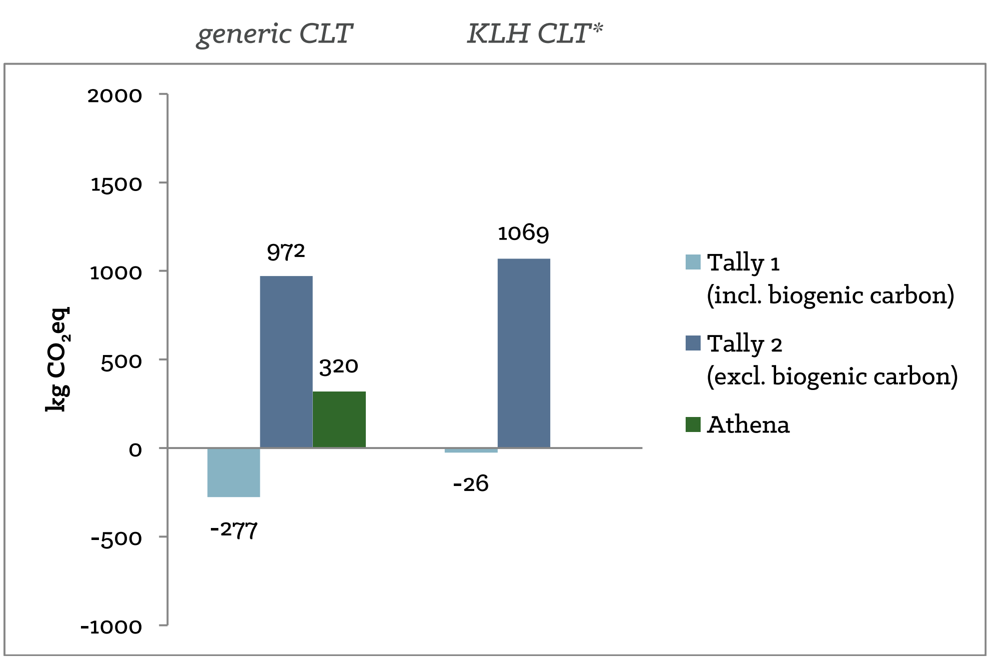
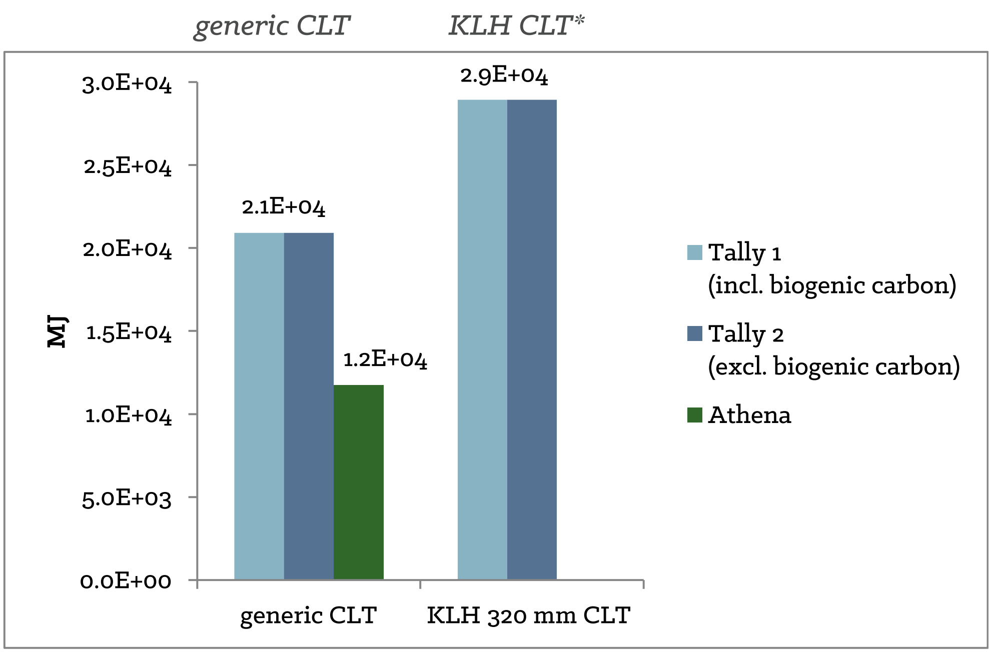


Figure 7 GWP (kg CO_2 eq) of CLT wall: life cycle stages **A, C, & D**



**KLH CLT is a manufacturer-specific CLT option only available in Tally, not Athena IE.*

Figure 8 Primary Energy Demand (MJ) of CLT wall: life cycle stages **A & C**

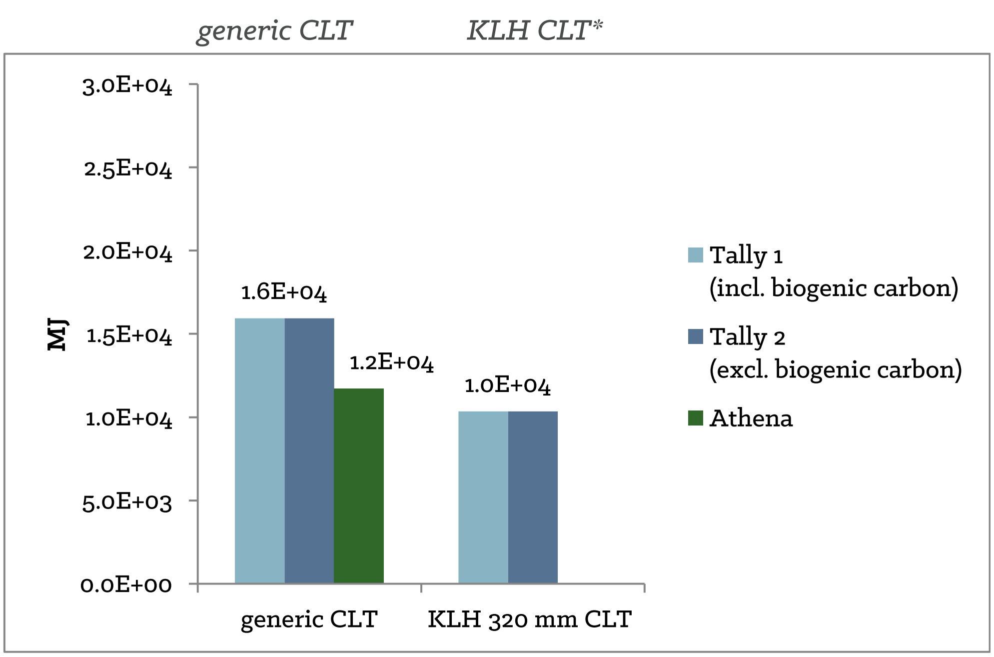


Figure 9 Primary Energy Demand (MJ) of CLT wall: life cycle stages **A, C, & D**

WBLCA CASE STUDIES

CASE STUDY 1

Exterior rendering of District Office, courtesy of Hacker

WBLCA OF DISTRICT OFFICE

Building Description

District Office is a six story, 90,400 sf (105,890 sf / 9837.5 sm including parking) mixed-use building in Portland, Oregon. Five floors of creative office space top a ground floor for retail and a below-ground parking garage. Several double height office spaces provide daylighting, connections, and views within and beyond the building (Wilson, 2018).

Glulam columns and beams form the primary structure, and the floors are 3 layer CLT panels with 3" concrete toppings. The core walls and foundations are reinforced concrete.

Goal and Scope

This study contains multiple parallel WBLCA results using Tally® and Athena Impact Estimator (IE) — one Tally result including biogenic carbon, one Tally result excluding biogenic carbon, and one result from Athena IE. The primary goal of this WBLCA is to determine the approximate environmental impacts of an office building that uses CLT. A secondary goal is to understand how different software options may influence estimated environmental impacts, especially global warming potential. The scope of this WBLCA is the building's structural Revit model, which includes floors, columns, beams, cores, foundations, and the roof. It does not include the enclosure or non-structural interior partitions. The assessment scope also excludes metal connections (nails, screws, bolts, etc.), sealants, and finishes.

Completion
2019 (estimated)

Location
Portland, Oregon, USA

Mixed Use
Commercial Office + Retail

Building Type
III-A Sprinklered

Building Area
105,890 gsf (9838 gsm)

Design and Engineering
Hacker (Architecture)
KPFF (Structural)
PAE Consulting Engineers (MEP)
ESA (Landscape)
Humber Design Group (Civil)

General Contracting
Andersen Construction

Developers
BEAM, UD+P

The reference study period for this WBLCA is the reference service life of the building, which is assumed to be 75 years. The square footage used for this WBLCA is 105,890 sf, which includes the unconditioned parking floor.

The primary **system boundary** for this WBLCA is cradle-to-grave, with the exclusion of the B1-B7 use stages of the building life cycle: Installed product in use (B1), Maintenance (B2), Repair (B3), Replacement (B4), Refurbishment (B5), Operational Energy Usage (B6) and Operational Water Usage (B7). The structure of the building is assumed to not need any maintenance during the building's lifespan. This modified cradle-to-grave system boundary encompasses the environmental impacts associated with extraction of raw materials, manufacturing of materials, transportation to construction site, and material disposal. A cradle-to-cradle system boundary, which includes Module D: impacts beyond the system boundary, is also calculated and presented in this case study. This module assigns value to the consequential avoided fossil fuel emissions from end-of-life material decisions, such as the potential avoided fossil fuel emissions resulting from incinerating wood or from recycling materials. However, the impacts of this stage are less certain, as they depend upon consequences in other product systems (i.e. that burning wood for fuel leads to less fossil fuel use).

*"The **system boundary** determines which unit processes shall be included within the LCA. The selection of the system boundary shall be consistent with the goal of the study" (ISO, 2006)***.**

Methodology

For this case study, the software program Tally and the software program Athena IE generated multiple whole building life cycle assessment (WBLCA) reports. First, a Revit model was created based on the building's construction documents. Then, Revit materials were assigned specifications in the Autodesk Revit add-in Tally, outputting a pdf and excel report. With the Tally report's information, another WBLCA was put together in the Athena IE software.

A key difference between inputs is Athena's addition of construction waste factors (generally ranging from 0.01 to 0.05), which cannot be manually overridden, so Athena may have slightly higher mass calculations in many cases. However, in other cases, entering Tally's material volume into Athena results in a slightly lower material mass than Tally's value — presumably due to different material density assumptions.

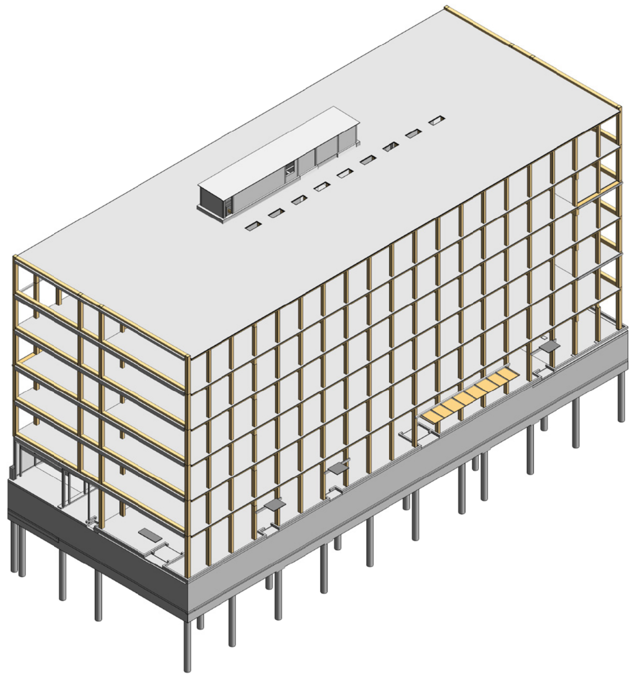


Figure 1.1 Structure of District Office, image courtesy of Hacker

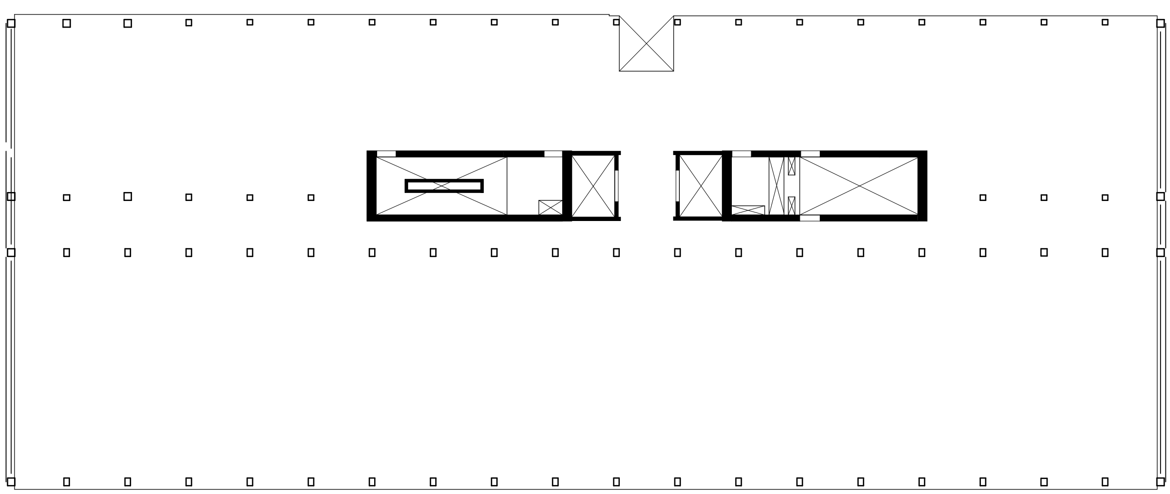


Figure 1.2 Structure Plan - Typical Office Floor (n.t.s.), image courtesy of Hacker

Tally and Athena's different material calculation, methodologies, and databases produce varying WBLCA results, but neither software consistently produces higher or lower results. For each environmental impact category, Tally and Athena's WBLCA data values are reassembled in new bar charts in this case study. For more detailed information on the methodology, refer to the case study series general methodology.

Assumptions

Both Athena IE and Tally have inherent assumptions and methods. Refer to the case study background for a description of key assumptions and differences. Material estimates are based on the structural engineering Revit model. Reinforced concrete is assumed to have a fly ash/slag content of less than 20%.

For both Athena IE and Tally, a custom transportation distance of 320 km for glulam and CLT was used, which is the distance from the CLT manufacturer D.R. Johnson to the construction site.

Results

District Office's environmental impacts are calculated for several impact categories: global warming potential, acidification potential, eutrophication potential, smog formation potential, and primary energy demand (embodied energy). Two software tools are used (Tally and Athena IE), and Tally generates two sets of impacts (including and excluding biogenic carbon). Each report shows cradle-to-grave impacts including and excluding module D, making a total of six calculation scenarios. Module D considers benefits beyond the system boundary, at the end of the building's life, such as the potential avoided fossil fuel emissions from burning wood or from recycling materials.

Discussion of Global Warming Potential

Global warming potential (see figure 1.3) varies significantly between Athena and Tally, between Tally biogenic options, and with the inclusion or exclusion of module D. Including module D, Athena has the lowest calculated global warming potential of 90 kg CO_2 eq/m^2. This is approximately half of 186 kg CO_2 eq/m^2, Tally 1's GWP that includes biogenic carbon and module D. The largest GWP is 300 kg CO_2 eq/m^2, which is calculated with Tally, and excludes biogenic carbon and module D.

Excluding module D, Athena's GWP is 18% higher than Tally 1's GWP but 26% lower than Tally 2's GWP. When comparing results between Tally options for excluding and including biogenic carbon, Tally 2

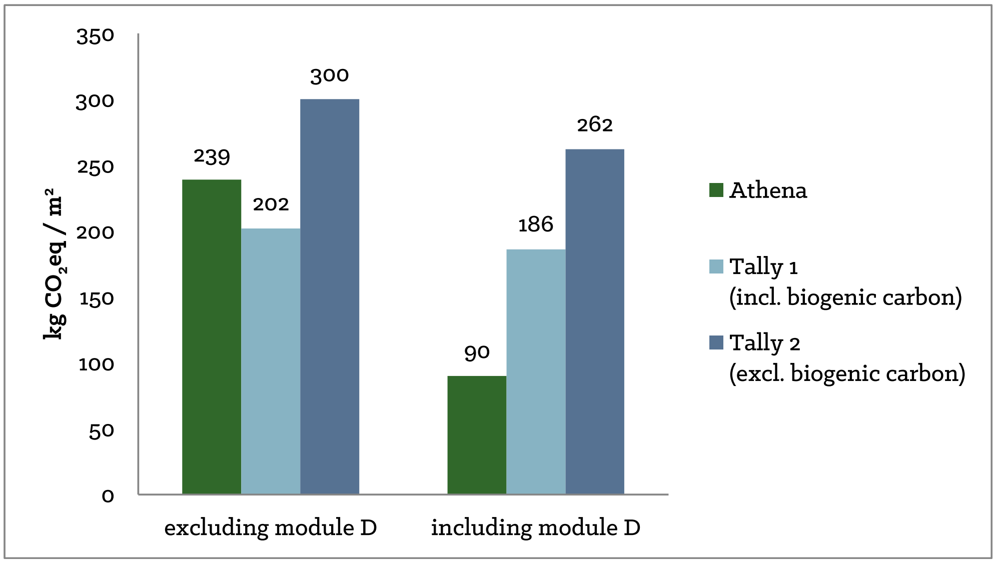


Figure 1.3 Global Warming Potential (kg CO_2 eq/m^2)

Global warming potential *measures the sum of greenhouse gas emissions. This impact category encompasses the emissions of CO_2 as well as other greenhouse gases: CH_4, N_2O, SF_6, PFC and HFC, which are converted into the quantity of CO_2 that would lead to the equivalent amount of global warming potential (IPCC, 2018).*

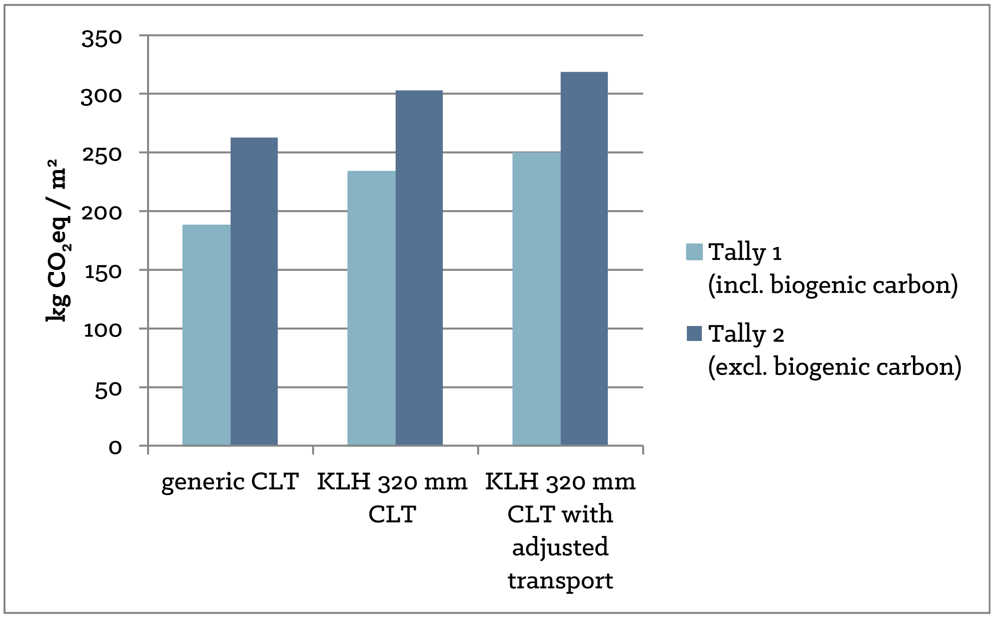
(excluding biogenic carbon) results in a GWP that is approximately 41-49% higher than Tally 1 (including biogenic carbon), whether or not module D is included.

Global Warming Potential: Sensitivity to CLT Manufacturer Choice & Transport Distance

Using Tally, a sensitivity analysis of the CLT panel's global warming potential shows how the GWP might change if a hypothetical alternate CLT manufacturer was selected and if transportation came from this alternate manufacturing location in Europe. In Tally, one can choose between a generic CLT material, which is based on adjusted North American glulam data, and a CLT material from the Austrian manufacturer KLH. For this sensitivity analysis, the GWP of District Office is calculated for three CLT scenarios. The first scenario assumes the generic CLT (which is analyzed in the rest of the case study), the second uses KLH's CLT (same transportation distance as scenario 1), and the third uses KLH's CLT and adds increased transportation due to KLH's Austrian manufacturing location. The second scenario increased the overall GWP by 25% when including biogenic carbon and by 15% when excluding biogenic carbon. The third scenario increased the overall GWP by 33% when including biogenic carbon and by 21% when excluding biogenic carbon. Refer

The adjusted transport distance covers approximate transportation from KLH's CLT factory in Teufenbach-Katsch, Austria to Portland, Oregon:

~ 750 km truck
~ 6,520 km container ship
~ 4,700 km train



GWP in figure 4 includes life cycle stages A-D.

Figure 1.4 Sensitivity to CLT Manufacturer Selection and Transportation: Global Warming Potential (kg CO_2 eq/m^2)

to the introduction for more information on the comparative impacts of a single CLT panel.

Discussion of other Environmental Impacts

The impacts of acidification potential, eutrophication potential, and smog formation potential exhibit some general trends. Generally, Athena's estimated impacts are higher than Tally's, with the exception of acidification potential when module D is excluded. For acidification, Tally's impacts are almost identical to Athena's when excluding module D, but Athena's impacts are approximately 9% higher when including module D. For eutrophication, Athena's values are 37% higher when excluding module D and are 42% higher when including module D. For smog formation, Athena's impacts are 58% higher than Tally's when excluding module D, and 71% higher when including module D. The inclusion of module D only affects GWP and acidification potential.

With regard to primary energy demand, which is the embodied energy of a building, Tally's demand is higher when module D is excluded. However, when module D is included, the reverse is true: Athena's estimated primary energy demand is higher than Tally's.

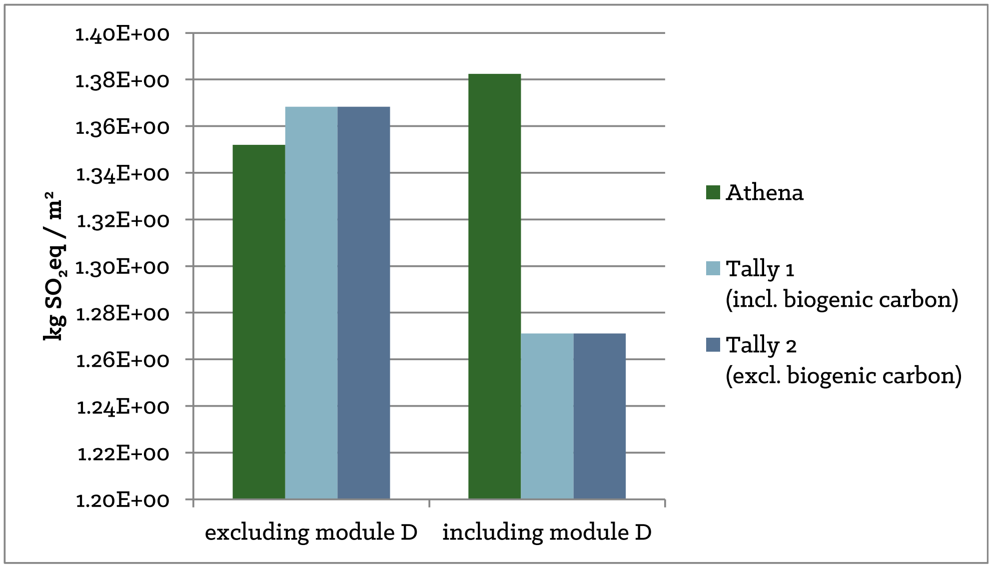


Figure 1.5 Acidification Potential (kg SO_2 eq/m^2)

Acidification *occurs when an increased concentration of hydrogen ions (H+) alters the acidity of water and soil systems. Acidification and the resulting acid rain can harm ecosystems, plants, animals, buildings, and monuments (Bare, 2012).*

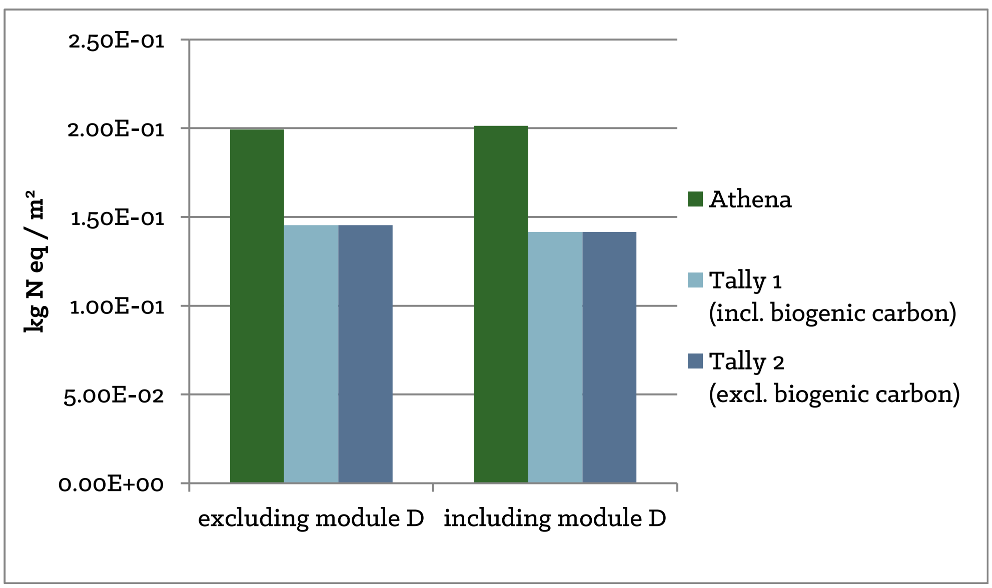


Figure 1.6 Eutrophication Potential (kg N eq/m^2)

Eutrophication *refers to the addition of mineral nutrients to soil or water, damaging ecological diversity. In water, nutrients of phosphorus (P) and nitrogen (N) can stimulate the growth of aquatic photosynthetic plant life (algae), which can decrease oxygen in the water and harm aquatic species (Lippiat, 2007).*

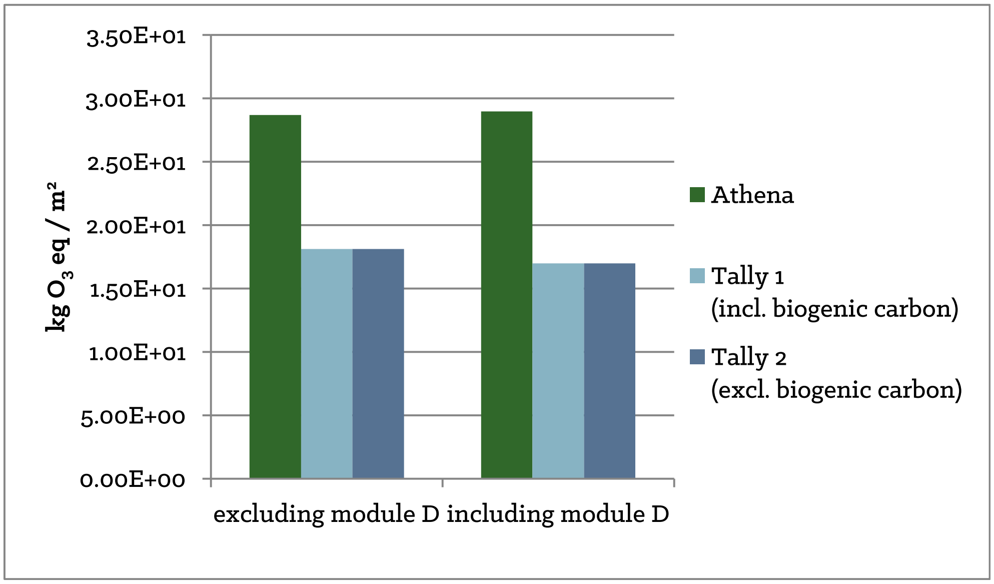


Figure 1.7 Smog Formation Potential (kg O_3 eq/m^2)

Photochemical smog *is the chemical reaction of sunlight, nitrogen oxides (NO_x) and volatile organic compounds (VOCs) in the atmosphere. Smog negatively impacts vegetation and causes human respiratory issues (Bare, 2012).*

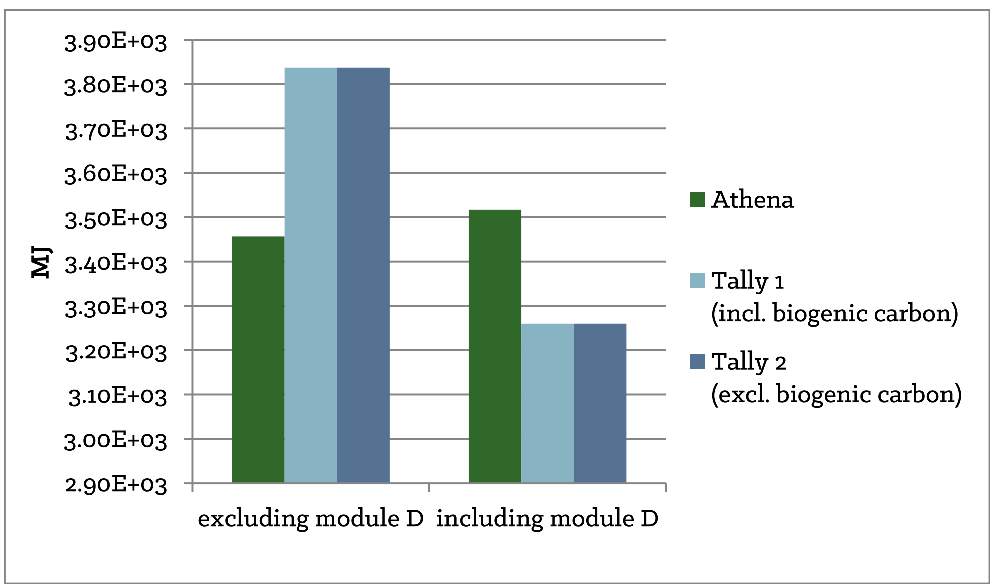


Figure 1.8 Primary Energy Demand (MJ/m^2)

Primary energy demand, *also known as "embodied energy" is a measure of the total primary energy needed to produce, transport, replace, and eventually demolish the building's materials. These numbers exclude operational energy (heating, cooling, etc.) and also exclude the energy expended by human labor.*

Lessons Learned & Opportunities

As this was the first WBLCA completed in the series, determining the best way to translate quantities from Tally to Athena required some troubleshooting. Athena has a bill of materials import feature, but certain errors prevented the use of that method. Instead, materials were manually translated from Athena to Tally using mass, volume, and density. Because District Office's structure was contained in a separate structural model, the scope of the WBLCA was limited to this structural model. In the future, the enclosure impacts could also be considered for a wider-scope WBLCA.

Summary

Biogenic carbon calculation methods and end-of-life assumptions heavily influence the magnitude of WBLCA impacts between scenarios and between Tally and Athena. The lowest calculated cradle-to-grave global warming potential is 90 kg CO_2 eq/m^2, calculated in Athena and including module D. The largest calculated GWP is 300 kg CO_2 eq/m^2, which is calculated with Tally, and excludes biogenic carbon and module D.

A similar precedent WBLCA and CLT building to District Office was published by Robertson, Lam, & Cole and is further described in the case study background (2012). Their studied office building, Discovery Place - Building 12, has the same general structural system as District Office — glulam columns and beams with CLT floors. Their estimated GWP of the structure and enclosure is 126 kg CO_2 eq./m^2 and has a cradle-to-gate system boundary (Robertson et al., 2012). However, this WBLCA is not directly comparable to District Office because of differences in system boundary and scope: District Office's GWP is cradle-to-grave and only includes structure.

The magnitude of other estimated environmental impacts, such as acidification and eutrophication potential, also vary between Tally and Athena IE. Eutrophication potential and smog formation potential are not very sensitive to the inclusion or exclusion of module D, but acidification potential and primary energy are. Within Tally, the inclusion or exclusion of biogenic carbon affects global warming potential but has no effect on the other environmental impact categories. For further discussion, refer to the case study series summary.

CASE STUDY 2

Exterior photo of Carbon 12 © Andrew Pogue

WBLCA of CARBON12

Building Description

Located in Portland, Oregon, Carbon12 is an eight story mixed-use building with seven condominium floors above a retail ground floor. The building features underground parking, solar-ready roof, and an elevator that opens directly into each unit. The building was permitted under the performance path for code approval — International Building Code Section 104.11 for Alternative Materials and Methods Requests (Structurlam, n.d., p. 2).

Glulam columns and beams form the primary structural frame for Carbon12, while steel framing makes up the building core elements. Floors are five layer CLT panels with additional sound insulation layers and a 1 1/2" lightweight concrete topping layer. The roof also uses five layer CLT panels. Structurlam was the manufacturer of both the glulam and the CLT panels, and they utilized beetle-kill pine wood in those products (Structurlam, n.d.).

Goals and Scope

This study contains multiple parallel WBLCA results using Tally® and Athena Impact Estimator (IE) — one Tally result including biogenic carbon, one Tally result excluding biogenic carbon, and one result from Athena IE. The primary goal of this WBLCA is to determine the approximate environmental impacts of a mixed use building that uses CLT. A secondary goal is to understand how different software options may influence estimated environmental impacts, especially global warming potential. The scope of this WBLCA is the building's structural Revit model, which includes floors, columns, beams, cores, foundations, and the roof. It does not include the enclosure or non-structural interior partitions. The assessment scope excludes metal connections (nails, screws, plates, bolts, etc.), sealants, and finishes.

The reference study period for this WBLCA, as well as the building's reference service life, is 75 years and is based on recommendations from ASTM E921 and ASHRAE 189.1 (Yang, 2018).

Completion
2018

Location
Portland, Oregon, USA

Mixed Use
Residential + Retail

Building Type
III-A Sprinklered

Building Area
32,499 gsf (3,019 gsm)

Design and Engineering
Path Architecture
Munzing Structural Engineering
Glumac (MEP)
KPFF (Civil)

General Contracting
Kasier Group

Developer
Kaiser Group

CLT Manufacturer
Structurlam

The primary **system boundary** for this WBLCA is cradle-to-grave, with the exclusion of the B1-B7 use stages of the building life cycle: Installed product in use (B1), Maintenance (B2), Repair (B3), Replacement (B4), Refurbishment (B5), Operational Energy Usage (B6) and Operational Water Usage (B7). The structure of a building is assumed to not need any maintenance during the building's lifespan. This modified cradle-to-grave system boundary encompasses the environmental impacts associated with extraction of raw materials, manufacturing of materials, transportation to construction site, and material disposal. A cradle-to-cradle system boundary, which includes Module D: impacts beyond the system boundary, is also calculated and presented in this case study. This module assigns value to the consequential avoided fossil fuel emissions from end-of-life material decisions, such as the potential avoided fossil fuel emissions resulting from incinerating wood or from recycling materials. However, the impacts of this stage are less certain, as they depend upon consequences in other product systems (i.e. that less fossil fuel will be burned if wood is burned for fuel).

*"The **system boundary** determines which unit processes shall be included within the LCA. The selection of the system boundary shall be consistent with the goal of the study" (ISO, 2006)***.**

Methodology

For this case study, the software program Tally and the software program Athena IE generated multiple whole building life cycle assessment (WBLCA) reports. First, Revit materials were assigned specifications in Tally, the Autodesk Revit add-in, and Tally produced a WBLCA pdf and excel report based on the quantities and materials. Then, using the material information from the Tally report, another WBLCA was assembled with the Athena IE software

A key difference between inputs is Athena's addition of construction waste factors (generally ranging from 0.01 to 0.05), which cannot be manually overridden, so Athena may have slightly higher mass calculations in many cases. However, in other cases, entering Tally's material volume into Athena results in a slightly lower material mass than Tally's value — presumably due to different material density assumptions.

Tally and Athena's differences of material calculation as well as other differences between the software (methodology and database sources) result in varying WBLCA results. Neither software consistently produced higher or lower results. To see the range of results, Tally and Athena's WBLCA data values are united in new

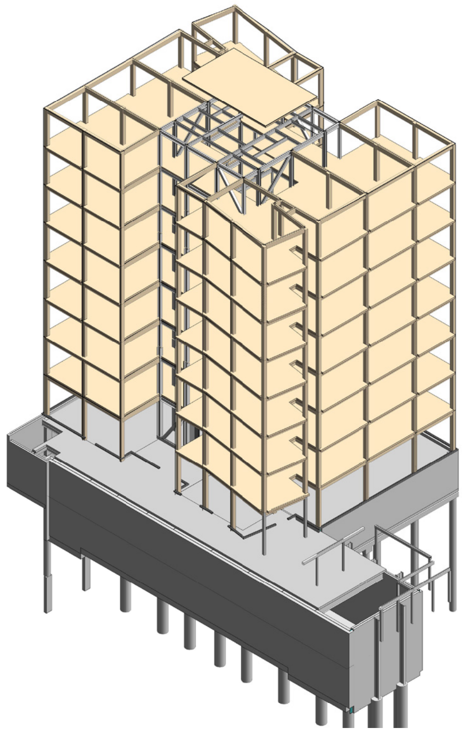


Figure 2.1 Structure of Carbon12

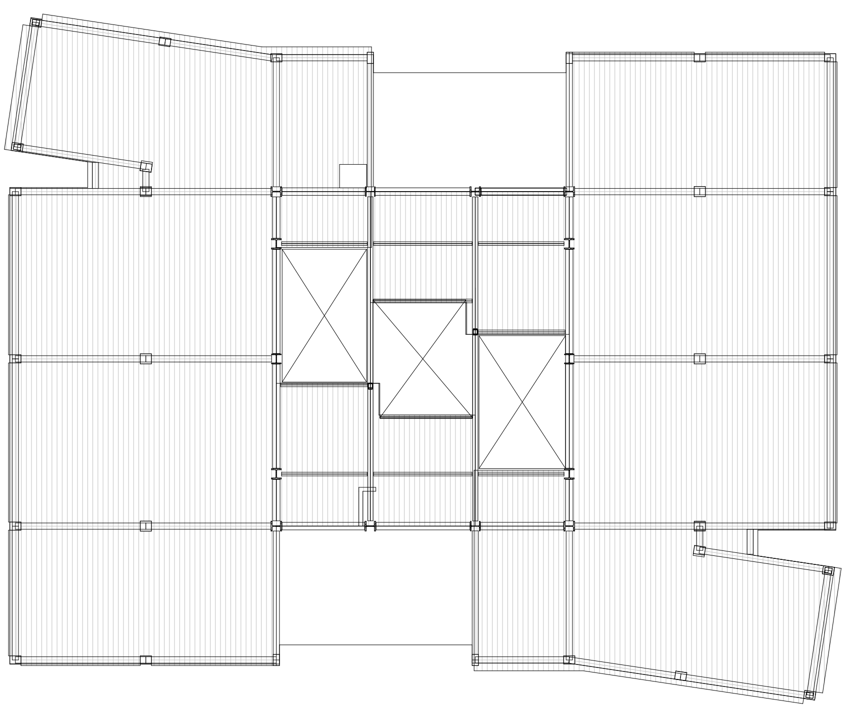


Figure 2.2 Structure Plan - Typical Condominium Floor (n.t.s.)

excel graphs. For more detailed information on the methodology, refer to the case study series general methodology.

Assumptions

Both Athena and Tally have inherent assumptions and methods. Refer to the case study background for a description of key assumptions and differences. Material estimates are based on the structural engineering Revit model. The digital construction documents file was also used to verify model intent. The Tally assessment and the Athena assessment use the same material quantity inputs. Reinforced concrete is assumed to have a fly ash/slag content of less than 20%.

For both Athena and Tally, a custom transportation distance of 745 km for glulam and CLT was used, which is the distance from Structurlam, the manufacturer, to the construction site in Portland.

Results

Carbon12's environmental impacts are calculated for several impact categories: global warming potential, acidification potential, eutrophication potential, smog formation potential, and primary energy demand (embodied energy). Two software tools are used (Tally and Athena IE), and Tally generates two sets of impacts (including and excluding biogenic carbon). Each report shows cradle-to-grave impacts including and excluding module D, making a total of six calculation scenarios.

Discussion of Global Warming Potential

Global warming potential (see figure 2.3) varies significantly between Athena and Tally, between Tally biogenic options, and with the inclusion or exclusion of module D. Including module D, Athena has the lowest calculated global warming potential of 185 kg CO_2 eq/m^2. This is only about 9% smaller than Tally 1's GWP that includes biogenic carbon and module D.

The largest GWP is 322 kg CO_2 eq/m^2, which is calculated with Tally, excluding biogenic carbon and module D. Excluding module D, Athena's GWP is almost identical to Tally 1's GWP but is 41% lower than Tally 2's GWP.

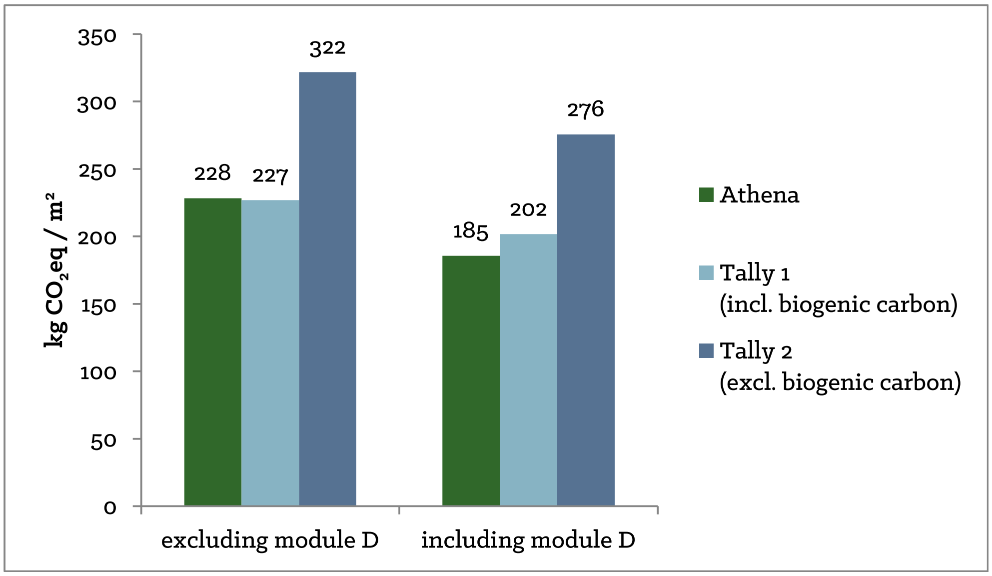


Figure 2.3 Global Warming Potential (kg CO_2 eq/m^2)

Global warming potential *measures the sum of greenhouse gas emissions. This impact category encompasses the emissions of CO_2 as well as other greenhouse gases: CH_4, N_2O, SF_6, PFC and HFC, which are converted into the quantity of CO_2 that would lead to the equivalent amount of global warming potential (ISO, 2018, p. 4).*

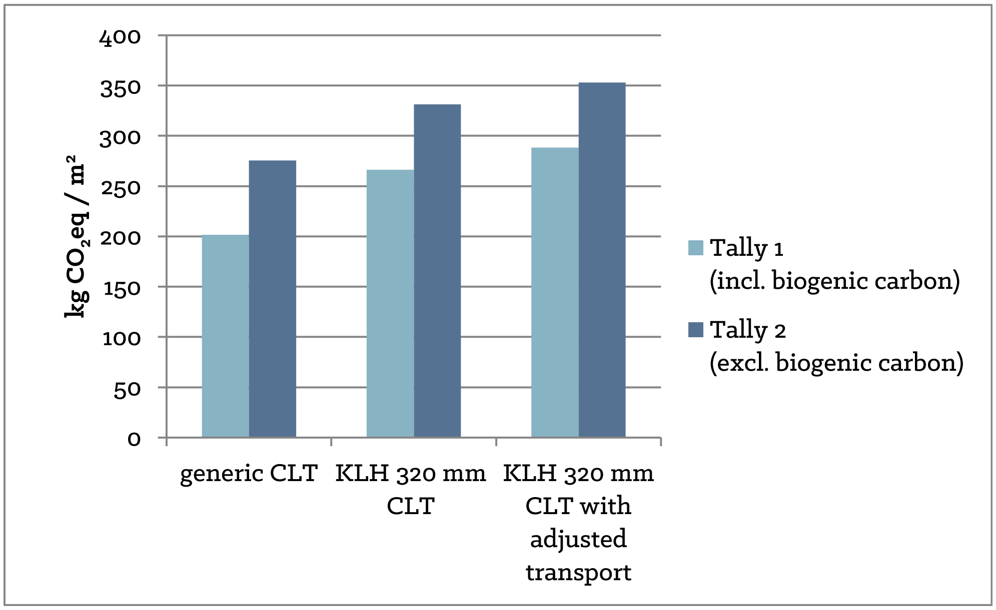
When comparing Tally 1 and Tally 2 results, Tally 2 (excluding biogenic carbon) results in a GWP that is 41% higher than Tally 1's when excluding module D, and 37% higher if including module D.

Global Warming Potential: Sensitivity to CLT Manufacturer Choice & Transport Distance

Using Tally, a sensitivity analysis of the CLT panel's global warming potential shows how the GWP might change if a hypothetical alternate CLT manufacturer was selected and if transportation came from this alternate manufacturing location in Europe. In Tally, one can choose between a generic CLT material, which is based on adjusted North American glulam data, and a CLT material from the Austrian manufacturer KLH. For this sensitivity analysis, the GWP of Carbon12 is calculated for three CLT scenarios. The first assumes the generic CLT (which is analyzed in the rest of the case study), the second uses KLH's CLT (same transportation distance as scenario 1), and the third uses KLH's CLT and adds increased transportation due to KLH's Austrian manufacturing location. The second scenario increased the overall GWP by 32% when including biogenic carbon and by 20% when excluding biogenic carbon. The

The adjusted transport distance covers approximate transportation from KLH's CLT factory in Teufenbach-Katsch, Austria to Portland, Oregon:

~ 750 km truck
~ 6,520 km container ship
~ 4,700 km train



GWP in figure 4 includes life cycle stages A-D.

Figure 2.4 Sensitivity to CLT Manufacturer Selection and Transportation: Global Warming Potential (kg CO_2 eq/m^2)

third scenario increased the overall GWP by 43% when including biogenic carbon and by 28% when excluding biogenic carbon. Refer to the introduction for more information on the comparative impacts of a single CLT panel.

Discussion of other Environmental Impacts

For this WBLCA, for some categories, Athena's impacts are higher, while for others, Tally's impacts are higher. For acidification, Tally's impacts are 40% higher than Athena's when excluding module D, and 24% higher when including module D. For eutrophication, Athena and Tally's values are within 1-4%, depending on whether or not module D is included. For smog formation, Athena's impacts are 23% higher than Tally's when excluding module D, and 36% higher when including module D.

With regard to primary energy demand, which is the embodied energy of a building, Tally's energy demand is 22% higher than Athena's when excluding module D, and 6% higher if including module D.

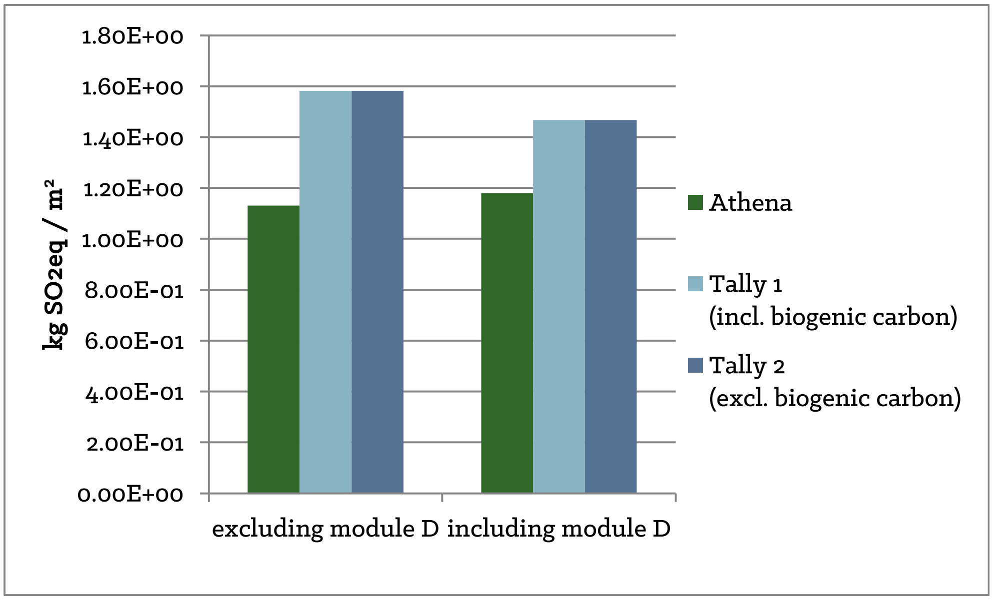


Figure 2.5 Acidification Potential (kg SO_2 eq/m^2)

Acidification *occurs when an increased concentration of hydrogen ions (H+) alters the acidity of water and soil systems. Acidification and the resulting acid rain can harm ecosystems, plants, animals, buildings, and monuments (Bare, 2012).*

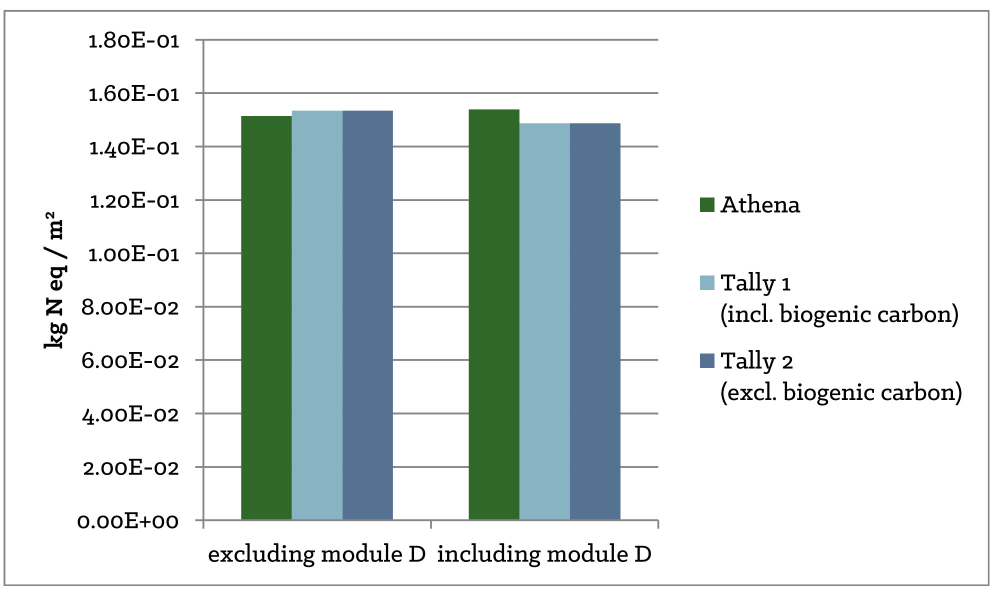


Figure 2.6 Eutrophication Potential (kg N eq/m^2)

Eutrophication *refers to the addition of mineral nutrients to soil or water, damaging ecological diversity. In water, nutrients of phosphorus (P) and nitrogen (N) can stimulate the growth of aquatic photosynthetic plant life (algae), which can decrease oxygen in the water and harm aquatic species (Lippiat, 2007).*

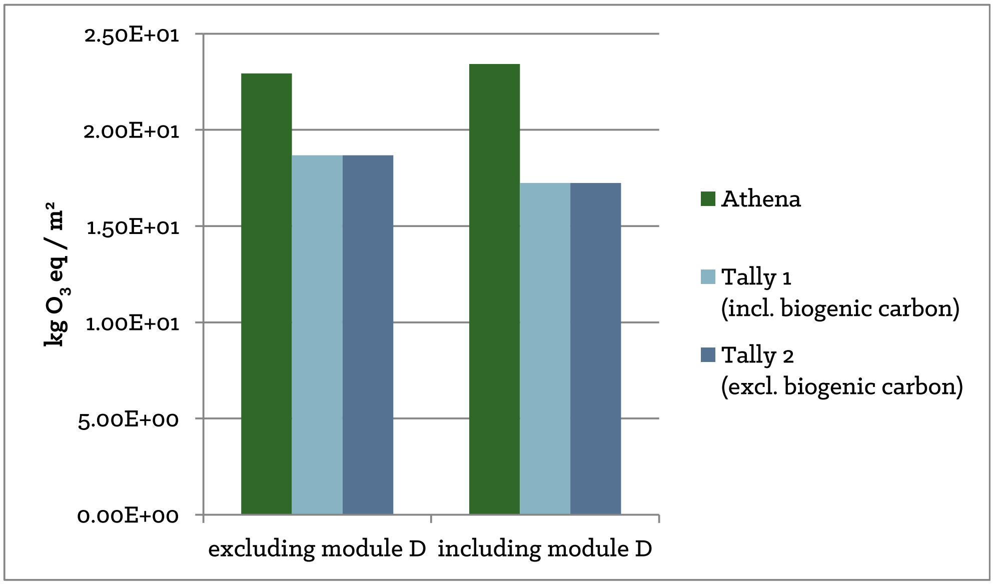


Figure 2.7 Smog Formation Potential (kg O_3 eq/m2)

Photochemical smog *is the chemical reaction of sunlight, nitrogen oxides (NO_x) and volatile organic compounds (VOCs) in the atmosphere. Smog negatively impacts vegetation and causes human respiratory issues (Bare, 2012).*

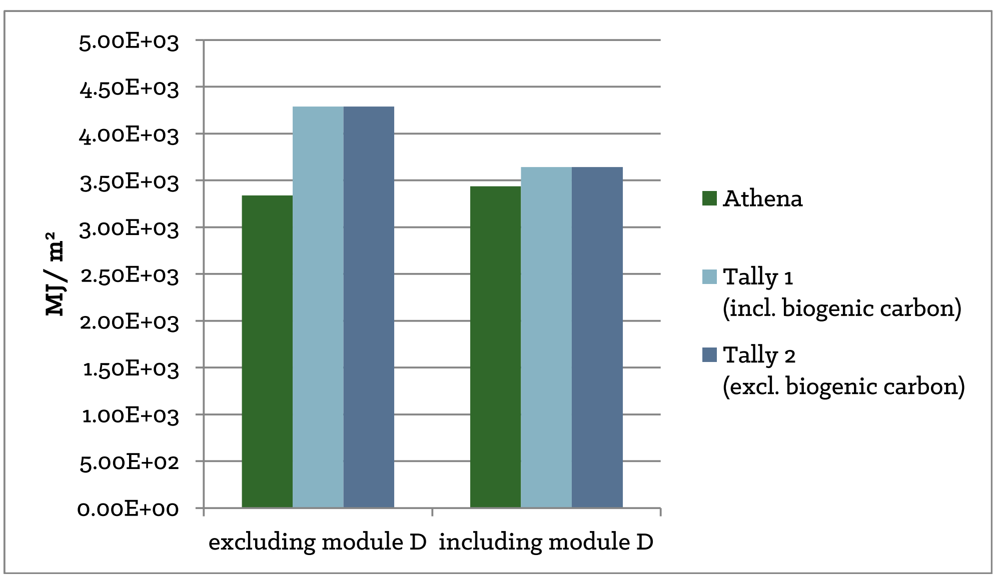


Figure 2.8 Primary Energy Demand (MJ/m^2)

Primary energy demand, *also known as "embodied energy" is a measure of the total primary energy needed to produce, transport, replace, and eventually demolish the building's materials. These numbers exclude operational energy (heating, cooling, etc.) and the energy expended by human labor.*

Lessons Learned & Opportunities

Because Carbon12's structure was contained in a separate structural Revit model, the scope of the WBLCA was limited to this structural model. In the future, the enclosure impacts could also be considered for a wider-scope WBLCA. For more information on general lessons learned and opportunities, refer to the series summary.

Summary

The magnitude of WBLCA impacts including and excluding module D, as well as between Tally and Athena, is heavily influenced by biogenic carbon calculation methods and end-of-life assumptions. The lowest calculated cradle-to-grave global warming potential is 186 kg CO_2 eq/m^2, calculated in Athena and including module D. The largest calculated GWP is 322 kg CO_2 eq/m^2, which is calculated with Tally, excluding biogenic carbon and module D.

The magnitude of other estimated environmental impacts, such as acidification and eutrophication potential, also vary between Tally and Athena. For some categories, Tally's impacts are higher, and Athena's impacts are higher for others. Some impacts are sensitive to the inclusion or exclusion of module D, while others are not. Environmental impacts are not sensitive to the inclusion or exclusion of biogenic carbon, other than global warming potential.

For the final series conclusion and discussion, refer to the general summary at the end of the case study series.

CASE STUDY 3

Exterior rendering of CLT Parking Garage, courtesy of SRG Partnership

WBLCA of GLENWOOD CLT PARKING GARAGE

Building Description

Glenwood CLT Parking Garage will be a new parking facility for the city of Springfield, in central Oregon. The garage contains four floors of parking with a ground floor retail space. While most parking garages are built exclusively in concrete, SRG has designed a garage using CLT and other wood structural elements. The five layer CLT floor panels are supported by glulam columns and beams. A 3" layer of synthetic fiber-reinforced concrete tops the CLT floors, which are left exposed on the underside to create an unusually beautiful garage interior. A façade of overlapping transparent glass panels will help protect the structure from the rain.

Goals and Scope

This study contains multiple parallel WBLCA results using Tally® and Athena IE — one Tally result including biogenic carbon, one Tally result excluding biogenic carbon, and one result from Athena IE. The primary goal of this WBLCA is to determine the approximate environmental impacts of a parking garage with CLT as a structural material. A secondary goal is to understand how different software options may influence estimated environmental impacts, especially global warming potential. The scope of this WBLCA is the building's structural Revit model, which includes floors, columns, beams, cores, foundations, and the roof. It does not include non-structural interior partitions. The assessment scope excludes metal connections (nails, screws, plates, bolts, etc.), sealants, and finishes.

The reference study period for this WBLCA, as well as the building's reference service life, is 75 years and is based on recommendations from ASTM E921 and ASHRAE 189.1 (Yang, 2018).

Completion
2020 (estimated)

Location
Springfield, Oregon, USA

Use
Parking Garage

Building Area
194,999 sf (18,116 sm)

Design and Engineering
SRG Partnership (Architecture)
KPFF (Structural)

Client
City of Springfield

CLT Manufacturer
D.R. Johnson

The primary **system boundary** for this WBLCA is a cradle-to-grave, with the exclusion of the B1-B7 use stages of the building life cycle: Installed product in use (B1), Maintenance (B2), Repair (B3), Replacement (B4), Refurbishment (B5), Operational Energy Usage (B6) and Operational Water Usage (B7). This modified cradle-to-grave system boundary encompasses the environmental impacts associated with extraction of raw materials, manufacturing of materials, transportation to construction site, and material disposal. A cradle-to-cradle system boundary, which includes Module D: impacts beyond the system boundary, is also calculated and presented in this case study. This module assigns value to the consequential avoided fossil fuel emissions from end-of-life material decisions, such as the potential avoided fossil fuel emissions resulting from incinerating wood or from recycling materials. However, the impacts of this stage are less certain, as they depend upon consequences in other product systems (i.e. that less fossil fuel will be burned if wood is burned for fuel).

"The ***system boundary*** *determines which unit processes shall be included within the LCA. The selection of the system boundary shall be consistent with the goal of the study" (ISO, 2006)***.**

Methodology

For this case study, the software program Tally and the software program Athena IE generated multiple whole building life cycle assessment (WBLCA) reports. First, Revit materials were assigned specifications in Tally, the Autodesk Revit add-in, and Tally produced a WBLCA pdf and excel report based on the quantities and materials. Then, using the material information from the Tally report, another WBLCA was assembled with the Athena IE software.

A key difference between inputs is Athena 's addition of construction waste factors (generally ranging from 0.01 to 0.05), which cannot be manually overridden, so Athena may have slightly higher mass calculations in many cases. However, in other cases, entering Tally's material volume into Athena results in a slightly lower material mass than Tally's value — presumably due to different material density assumptions.

Tally and Athena's differences of material calculation as well as other differences between the software (methodology and database sources) produce varying WBLCA results. Neither software consistently produced higher or lower results. To see the range of results, Tally and Athena's WBLCA data values are united in new excel graphs. For the extended methodology, refer to the series background.

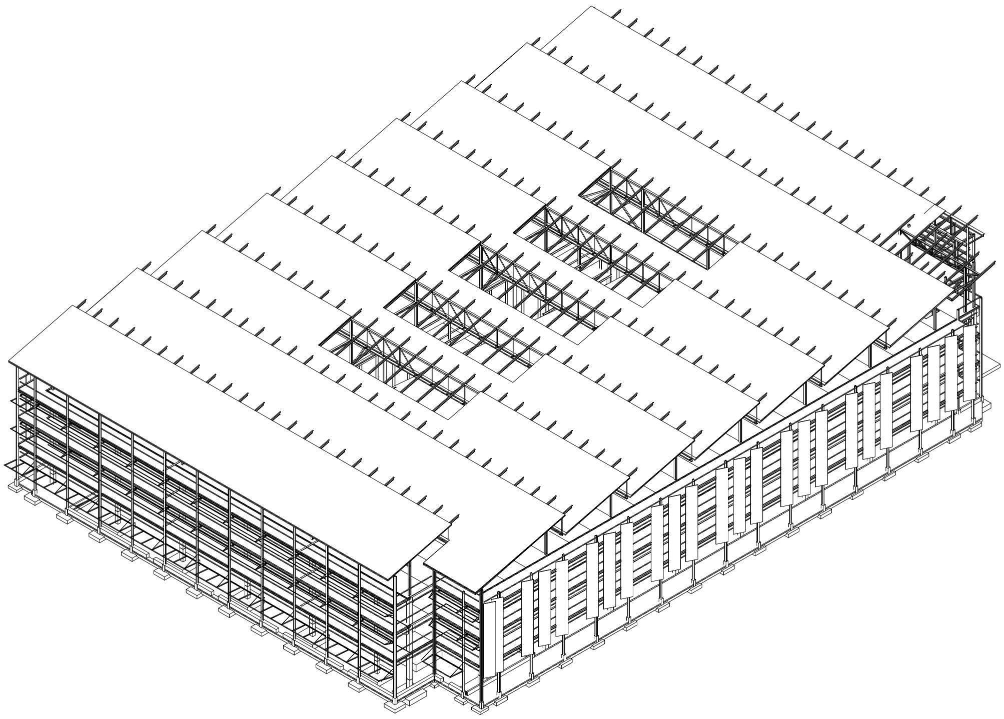


Figure 3.1 Structure of Glenwood Parking Garage (note: WBLCA excludes vertical screens on the facade)

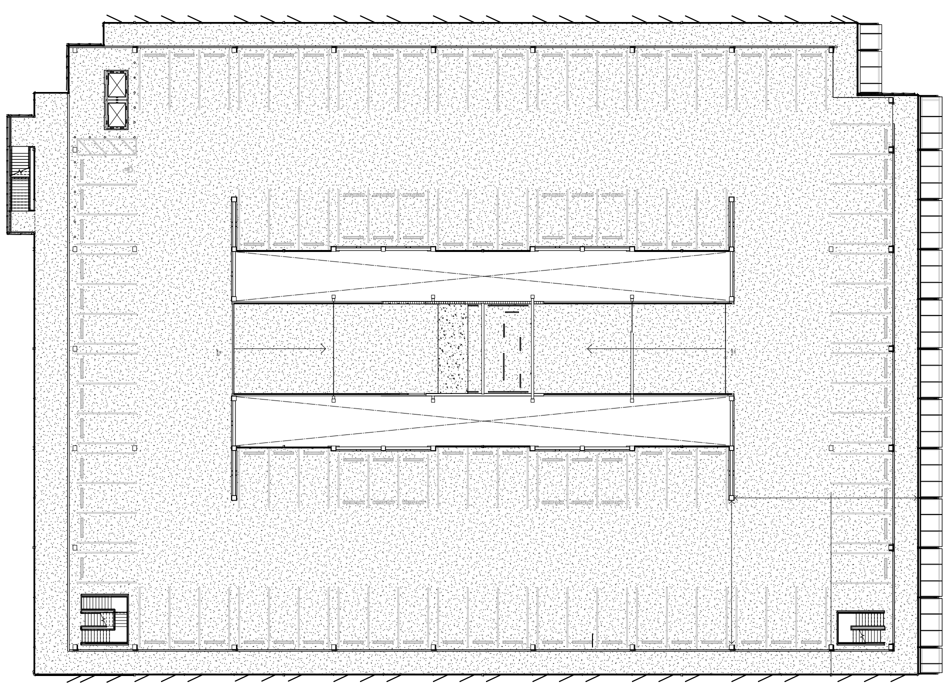


Figure 3.2 Structure Plan - Typical Floor (n.t.s.)

Assumptions

Both Athena and Tally have inherent assumptions and methods. Refer to the case study background for detailed information about the two software programs. Material estimates are based on the structural engineering Revit model. The digital construction documents file was also used to verify model intent. Reinforced concrete is assumed to have a fly ash/slag content of less than 20%.

For both Athena and Tally, a custom transportation distance of 146 km for glulam and CLT was used, which is the distance from D.R. Johnson, the manufacturer, to the site in Sprinfield, Oregon.

Results

Glenwood Parking Garage's environmental impacts are calculated for several impact categories: global warming potential, acidification potential, eutrophication potential, smog formation potential, and primary energy demand (embodied energy). Two software tools are used (Tally and Athena), and Tally generates two sets of impacts (including and excluding biogenic carbon). Each report shows cradle-to-grave impacts including and excluding module D, making a total of six calculation scenarios.

Discussion of Global Warming Potential

Global warming potential (see figure 3.3) varies significantly between Athena and Tally, between Tally biogenic options, and with the inclusion or exclusion of module D. Including module D, Athena has the lowest calculated global warming potential of 52 kg CO_2 eq/m^2. This is about 78% smaller than Tally 1's GWP that includes biogenic carbon and module D. The largest GWP is 214 kg CO_2 eq/m^2, which is calculated with Tally, and excludes biogenic carbon and module D.

When comparing Tally's results for excluding and including biogenic carbon, Tally 2 (excluding biogenic carbon) results in a GWP that is approximately twice as large than Tally 1 (including biogenic carbon), whether or not module D is included. The inclusion of module D has the greatest impact on Athena's GWP; its inclusion reduces the GWP by more than half.

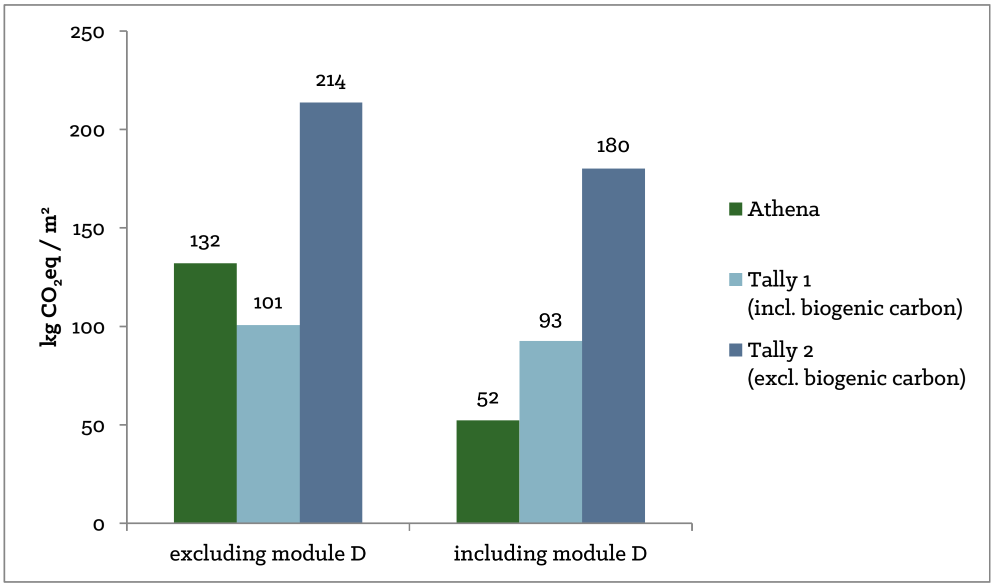


Figure 3.3 Global Warming Potential (kg CO_2 eq/m²)

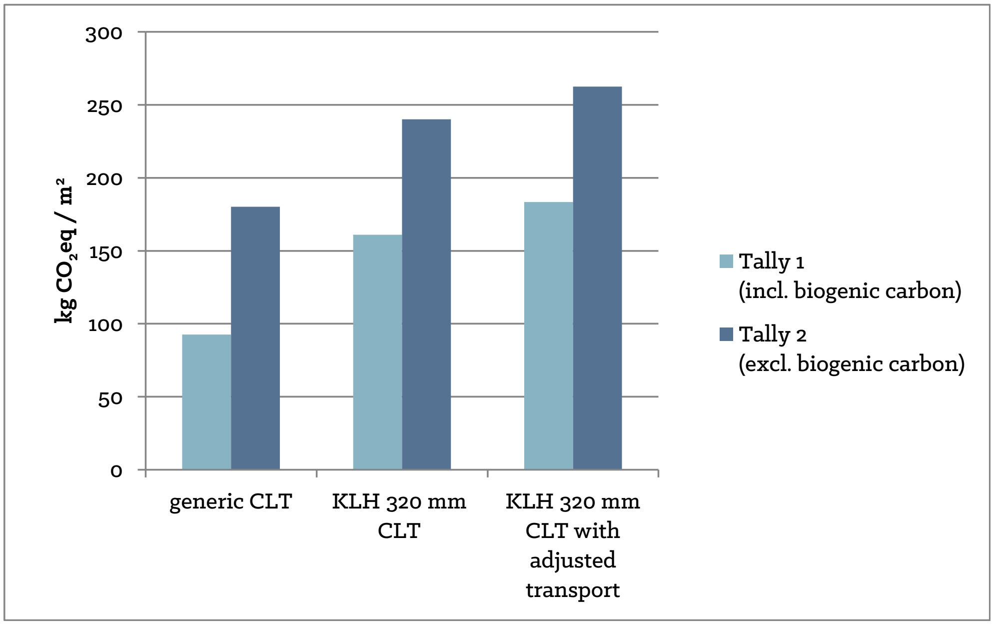
Global warming potential *measures the sum of greenhouse gas emissions. This impact category encompasses the emissions of CO_2 as well as other greenhouse gases: CH_4, N_2O, SF_6, PFC and HFC, which are converted into the quantity of CO_2 that would lead to the equivalent amount of global warming potential (ISO, 2018, p. 4).*

Global Warming Potential: Sensitivity to CLT Manufacturer Choice & Transport Distance

Using Tally, a sensitivity analysis of the CLT panel's global warming potential shows the influence of CLT manufacturer selection as well as transportation distance on the overall GWP. In Tally, one can choose between a generic CLT material, which is based on adjusted North American glulam data, and a CLT material from the Austrian manufacturer KLH. For this sensitivity analysis, the GWP of the Glenwood Parking Garage is calculated for three CLT scenarios. The first assumes the generic CLT (which is analyzed in the rest of the case study), the second uses KLH's CLT (same transportation distance as scenario 1), and the third uses KLH's CLT and adds increased transportation due to KLH's manufacturing location. The second scenario increased the overall GWP by 74% when including biogenic carbon and by 33% when excluding biogenic carbon. The third scenario increased the overall GWP by 98% when including biogenic carbon and by 46% when excluding biogenic carbon. Refer to the introduction for more information on the comparative impacts of a single CLT panel.

The adjusted transport distance covers approximate transportation from KLH's CLT factory in Teufenbach-Katsch, Austria to Springfield, Oregon:

~ 750 km truck
~ 6,520 km container ship
~ 4,700 km train



GWP in figure 4 includes life cycle stages A-D.

Figure 3.4 Sensitivity to CLT Manufacturer Selection and Transportation: Global Warming Potential (kg CO_2 eq/m^2)

Discussion of other Environmental Impacts

For this WBLCA, Tally's estimated impacts for environmental impacts other than GWP are higher than Athena's, other than smog formation potential. For acidification, Tally's impacts are 39% higher than Athena's when excluding module D, and 34% higher when including module D. For eutrophication, Tally's impacts are approximately 45% higher than Athena's. For smog formation, Athena's impacts are 24% higher than Tally's when excluding module D, and 36% higher if including module D.

With regard to primary energy demand (embodied energy), Tally's energy demand is 31% higher than Athena's when excluding module D, and 17% higher if including module D.

The inclusion of module D has little affect on the environmental impacts except GWP and primary energy demand. The inclusion or exclusion of biogenic carbon does not affect environmental impacts except for GWP.

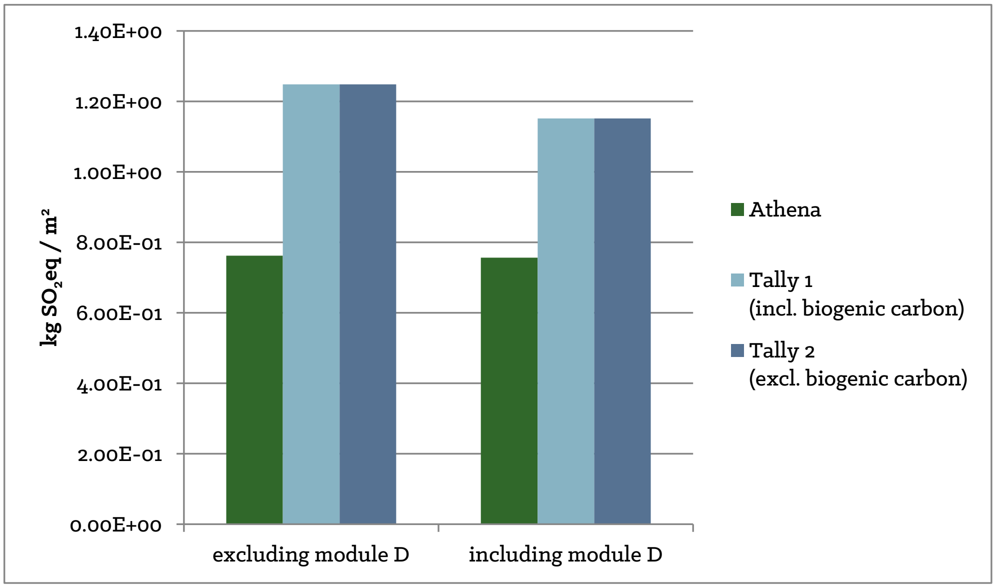


Figure 3.5 Acidification Potential (kg SO_2 eq/m^2)

Acidification *occurs when an increased concentration of hydrogen ions (H+) alters the acidity of water and soil systems. Acidification and the resulting acid rain can harm ecosystems, plants, animals, buildings, and monuments (Bare, 2012).*

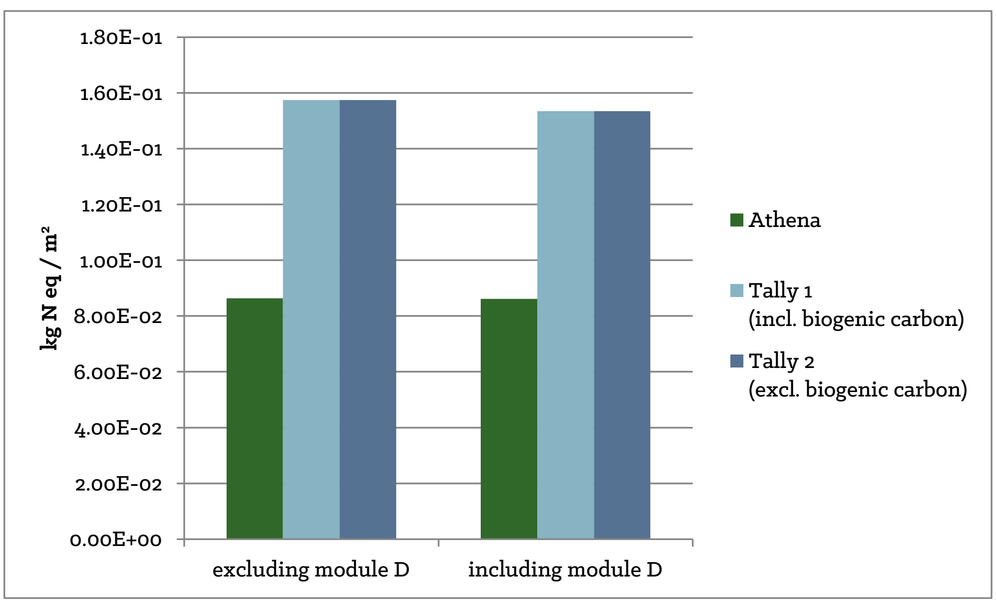


Figure 3.6 Eutrophication Potential (kg N eq/m^2)

Eutrophication *refers to the addition of mineral nutrients to soil or water, damaging ecological diversity. In water, nutrients of phosphorus (P) and nitrogen (N) can stimulate the growth of aquatic photosynthetic plant life (algae), which can decrease oxygen in the water and harm aquatic species (Lippiat, 2007).*

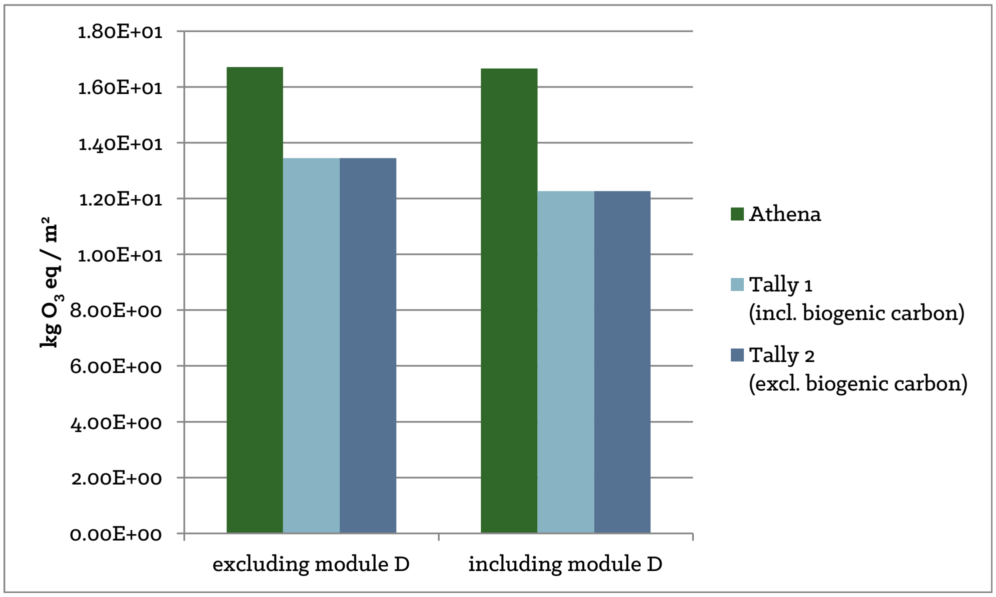


Figure 3.7 Smog Formation Potential (kg O_3 eq/m^2)

Photochemical smog *is the chemical reaction of sunlight, nitrogen oxides (NO_x) and volatile organic compounds (VOCs) in the atmosphere. Smog negatively impacts vegetation and causes human respiratory issues (Bare, 2012).*

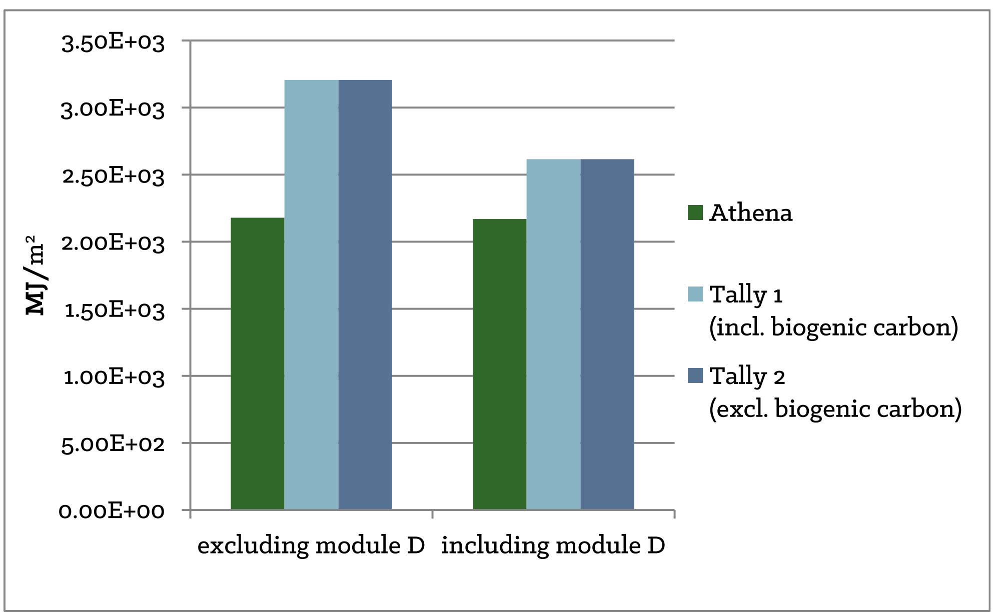


Figure 3.8 Primary Energy Demand (MJ/m^2)

Primary energy demand, *also known as "embodied energy" is a measure of the total primary energy needed to produce, transport, replace, and eventually demolish the building's materials. These numbers exclude operational energy (heating, cooling, etc.) and also exclude the energy expended by human labor.*

Lessons Learned & Opportunities

Refer to the series summary for general lessons learned and opportunities.

Summary

The magnitude of WBLCA impacts including and excluding module D, as well as between Tally and Athena, is heavily influenced by biogenic carbon calculation methods and end-of-life assumptions. The lowest calculated global warming potential is 52 kg CO_2 eq/m^2, calculated in Athena and including module D. The largest calculated GWP is 214 kg CO_2 eq/m^2, which is calculated with Tally, excluding biogenic carbon and module D.

The magnitude of other estimated environmental impacts was higher for Tally in all categories other than smog formation potential. Some impacts are sensitive to the inclusion or exclusion of module D, while others are not. Environmental impacts are not sensitive to the inclusion or exclusion of biogenic carbon, other than global warming potential. For the final series conclusion and discussion, refer to the general summary at the end of the case study series.

CASE STUDY 4

Exterior photo of CLTHouse © Lara Swimmer Photography

WBLCA of CLTHOUSE

Building Description

CLTHouse is one of the first residential buildings utilizing CLT in the state of Washington. The building's construction type is VB, using the alternative means and methods path for code approval of the CLT as a structural system.

The two story house includes a generous roof deck and basement bike storage, accessible from a central stair. Sixty-seven regionally-sourced CLT panels make up the second floor, interior walls, exterior walls, and roof. Other structural materials occur in limited amounts: concrete foundations and minimal steel structural support. In order to promote sustainable forest practices and offset the embodied carbon of the CLT panels, the owners ensured that the manufacturer replanted additional trees after harvest, beyond the usual one-to-one replanting. Interior walls are primarily three layer CLT panels with an interior whitewash finish consisting of a water-based paint and sealant top coats. The second floor CLT floor panels are five layers thick with an additional sealant top coat. The exterior walls have three layer CLT panels, and the roof has five layer CLT panels with additional insulation and enclosure layers.

Goals and Scope

This study contains multiple parallel WBLCA results using Tally® and Athena IE — one Tally result including biogenic carbon, one Tally result excluding biogenic carbon, and one result from Athena IE. The primary goal of this WBLCA is to determine the approximate environmental impacts of a single family residence that uses CLT.

Completion
2015

Location
Seattle, Washington, USA

Mixed Use
Residential (single family)

Building Type
VB

Building Area
1,483 gsf (137.8 gsm)

Design and Engineering
atelierjones, llc (Architecture)
Harriot Valentine Engineers (Structural Engineering)

General Contracting
Cascade Built

CLT Manufacturer
Structurlam

A secondary goal is to understand how different software options may influence estimated environmental impacts, especially global warming potential. The scope of this WBLCA is the building's Revit model, which includes foundation, structure, enclosure, roof, stairs, interior partitions, doors, and windows. It includes basic finishes such as paint and sealants on the CLT. It excludes metal connections (nails, screws, bolts, etc.), sitework, concrete formwork, ground floor decks, exterior planters, casework (cabinets/millwork), electrical, plumbing, mechanical components, and the roof's gutter.

The reference study period for this WBLCA, as well as the building's reference service life, is 75 years and is based on recommendations from ASTM E921 and ASHRAE 189.1 (Yang, 2018).

The primary **system boundary** for this WBLCA is cradle-to-grave, with the exclusion of B1 (Use), B6 (Operational Energy Usage), and B7 (Operational Water Usage). Case studies 1—3 excluded stage B impacts because the scope was limited to the structure of their respective buildings, due to the separated Revit model.. This case study has an expanded scope that includes the enclosure and some finishes, which would be subject to replacement or refinishing during a 75 year lifespan. The cradle-to-grave system boundary encompasses the environmental impacts associated with extraction of raw materials, manufacturing of materials, transportation to construction site, material repair/replacement, and material disposal. A cradle-to-cradle system boundary, which includes Module D: impacts beyond the system boundary, is also calculated and presented in this case study. This module assigns value to the consequential avoided fossil fuel emissions from end-of-life material decisions, such as the potential avoided fossil fuel emissions resulting from incinerating wood or from recycling materials. However, the impacts of this stage are less certain, as they depend upon future consequences in other product systems (i.e. that less fossil fuel will be burned if wood is burned for fuel).

*"The **system boundary** determines which unit processes shall be included within the LCA. The selection of the system boundary shall be consistent with the goal of the study" (ISO, 2006)*.

Methodology

For this case study, the software program Tally and the software program Athena IE generated multiple whole building life cycle assessment (WBLCA) reports. First, a Revit model was created based on the building's construction documents. Then, Revit materials were assigned specifications in the Autodesk Revit add-in Tally,

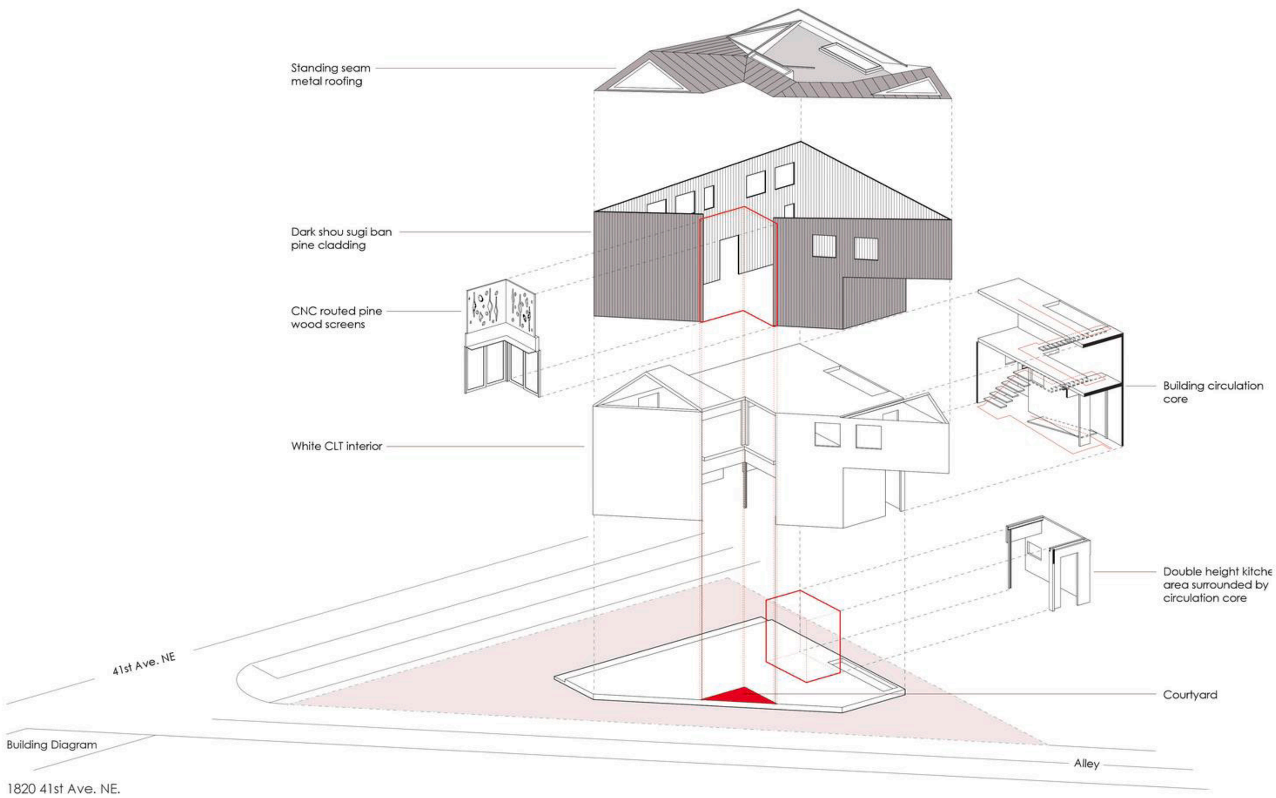


Figure 4.1 Diagram of CLTHouse © atelierjones

Figure 4.2 Construction of CLTHouse © atelierjones

outputting a pdf and excel report. With the Tally report's information, another WBLCA was put together in the Athena IE software.

A key difference between inputs is Athena's addition of construction waste factors (generally ranging from 0.01 to 0.05), which cannot be manually overridden, so Athena may have slightly higher mass calculations in many cases. However, in other cases, entering Tally's material volume into Athena results in a slightly lower material mass than Tally's value — presumably due to different material density assumptions.

Tally and Athena IE's differences of material calculation as well as other differences between the software (methodology and database sources) produce varying WBLCA results. Neither software consistently produced higher or lower results. To see the range of results, Tally and Athena IE's WBLCA data values are united in new excel graphs. For more detailed information on the methodology, refer to the case study series general methodology.

Assumptions

Both Athena and Tally have inherent assumptions and methods. Refer to the case study background for a description of key assumptions and differences. Material estimates are based on the Revit model. The digital construction documents file is a secondary information source for verification. The Tally assessment and the Athena assessment use the same material quantity inputs. Reinforced concrete is assumed to have a fly ash/slag content of less than 20%.

For both Athena and Tally, a custom transportation distance of 479 km for glulam and CLT was used, which is the distance from Structurlam, the manufacturer, to the construction site.

Results

CLTHouse's environmental impacts are calculated for several impact categories: global warming potential, acidification potential, eutrophication potential, smog formation potential, and primary energy demand (embodied energy). Two software tools are used (Tally and Athena IE), and Tally generates two sets of impacts (including and excluding biogenic carbon). Each of the three reports shows cradle-to-grave impacts including and excluding module D, making a total of six calculation scenarios.

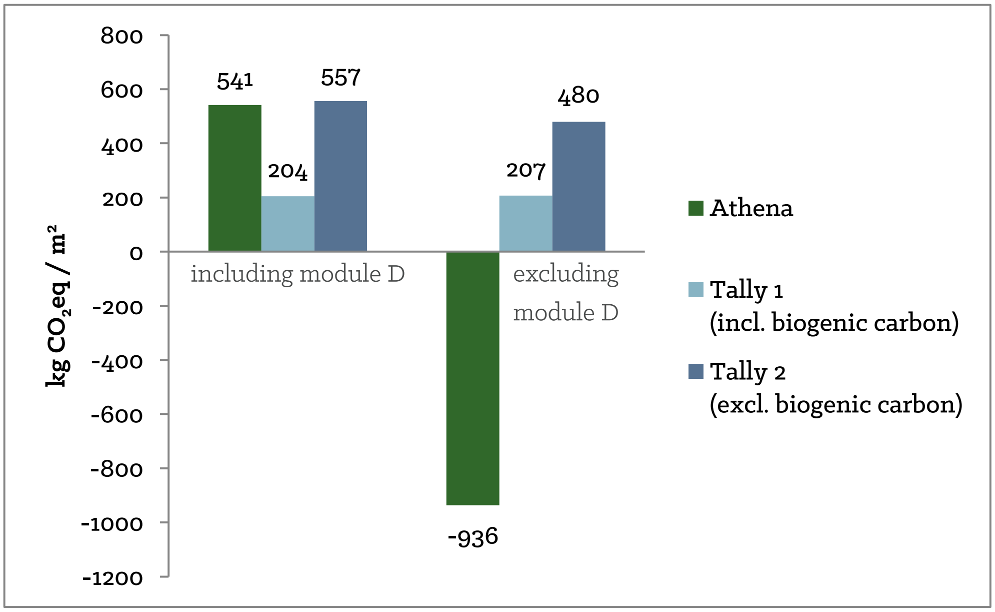


Figure 4.3 Global Warming Potential (kg CO_2 eq/m^2)

Global warming potential *measures the sum of greenhouse gas emissions. This impact category encompasses the emissions of CO_2 as well as other greenhouse gases: CH_4, N_2O, SF_6, PFC and HFC, which are converted into the quantity of CO_2 that would lead to the equivalent amount of global warming potential (ISO, 2018, p. 4).*

Discussion of Global Warming Potential

Estimates of global warming potential (see figure 4.3) ranges from a low of -936 kg CO_2 eq/m^2 to a high of 557 kg CO_2 eq/m^2. Including module D, Athena has the lowest calculated global warming potential of -936 kg CO_2 eq/m^2. Excluding module D, Athena's results (541 kg CO_2 eq/m^2) are close to Tally's results that exclude biogenic carbon (557 kg CO_2 eq/m^2). The largest GWP estimate is 557 kg CO_2 eq/m^2, which is calculated with Tally, and excludes biogenic carbon and module D.

When comparing Tally's results excluding and including biogenic carbon, Tally 2 (excluding biogenic carbon) results in a GWP that is approximately 173% larger than Tally 1 (including biogenic carbon) excluding module D. When including module D, Tally 2's results are 132% larger than Tally 1's.

Global Warming Potential: Sensitivity to CLT Manufacturer Choice & Transport Distance

Using Tally, a sensitivity analysis of the CLT panel's global warming potential shows how the GWP might change if a hypothetical alternate CLT manufacturer was selected and if transportation came from this alternate manufacturing location in Europe. In Tally, one can choose between a generic CLT material, which is based on

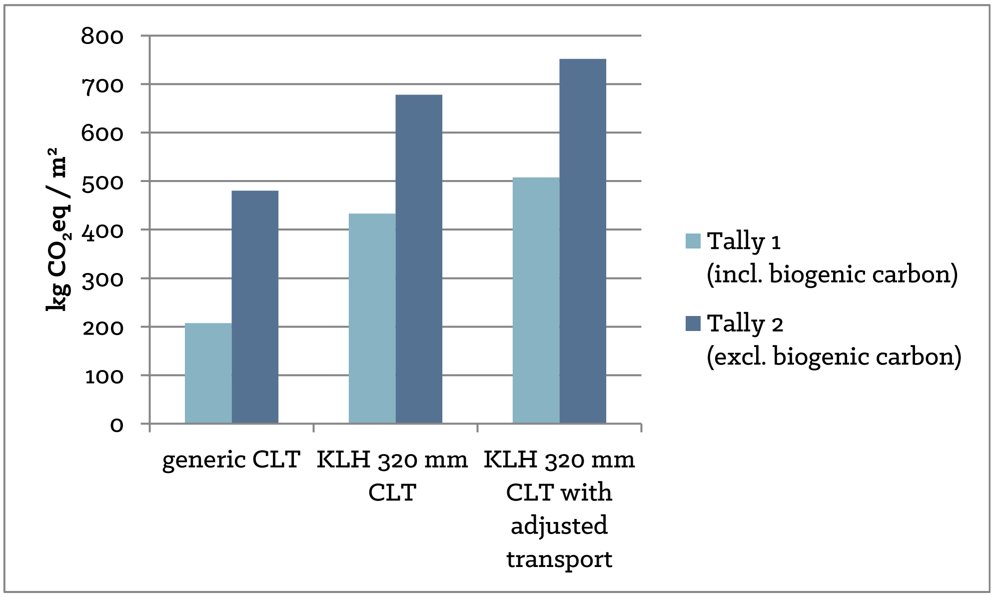


Figure 4.4 Sensitivity to CLT Manufacturer Selection and Transportation: Global Warming Potential (kg CO_2 eq/m^2)

GWP in figure 3 includes life cycle stages A-D.

adjusted North American glulam data, and a CLT material from the Austrian manufacturer KLH. For this sensitivity analysis, the GWP of CLTHouse is calculated for three CLT scenarios. The first assumes the generic CLT (which is analyzed in the rest of the case study), the second uses KLH's CLT (same transportation distance as scenario 1), and the third uses KLH's CLT and adds increased transportation due to KLH's Austrian manufacturing location. The second scenario increased the overall GWP by 109% when including biogenic carbon and by 41% when excluding biogenic carbon. The third scenario increased the overall GWP by 145% when including biogenic carbon and by 57% when excluding biogenic carbon.

The adjusted transport distance covers approximate transportation from KLH's CLT factory in Teufenbach-Katsch, Austria to Seattle, Washington

~ 750 km truck
~ 6,520 km container ship
~ 4,600 km train

Discussion of other Environmental Impacts

The impacts of acidification potential, eutrophication potential, and smog formation potential exhibit some general trends. Athena's estimated impacts are higher than Tally's. For acidification, Athena's impacts are 59% higher than Tally's if excluding module D, and 68% higher when including module D. For eutrophication, Athena's impacts are 69% higher than Tally's when excluding module D, and 73% higher when including module D. For smog formation, Athena's impacts are 249% higher than Tally's when excluding module D, and

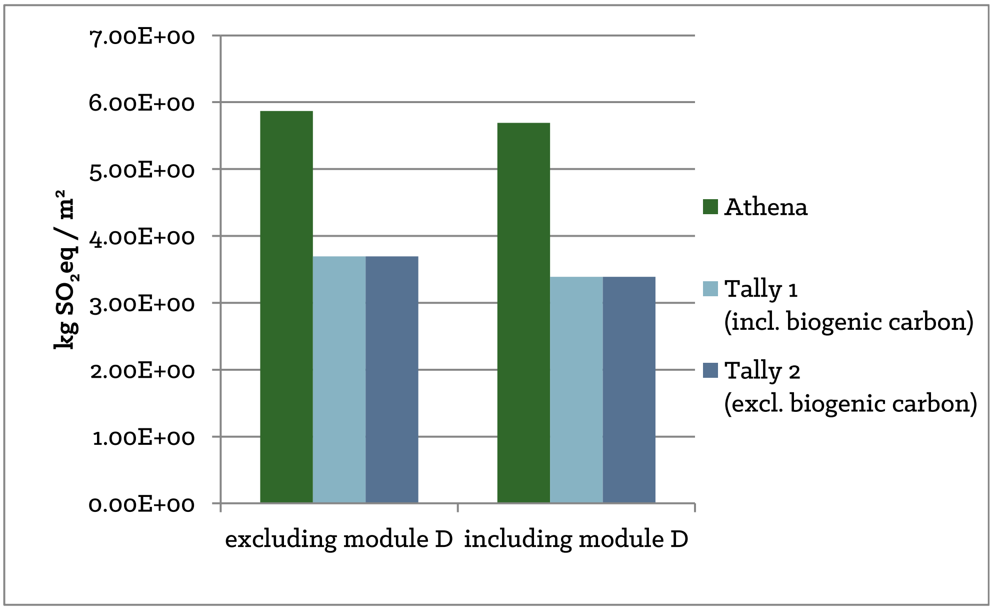


Figure 4.5 Acidification Potential (kg SO_2 eq/m^2)

Acidification *occurs when an increased concentration of hydrogen ions (H+) alters the acidity of water and soil systems. Acidification and the resulting acid rain can harm ecosystems, plants, animals, buildings, and monuments (Bare, 2012).*

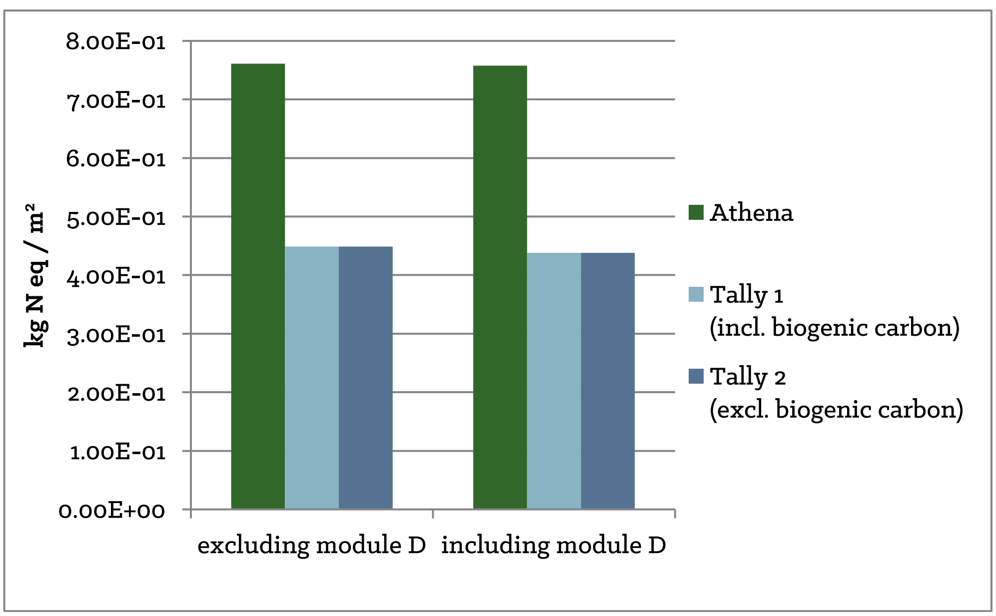


Figure 4.6 Eutrophication Potential (kg N eq/m^2)

Eutrophication *refers to the addition of mineral nutrients to soil or water, damaging ecological diversity. In water, nutrients of phosphorus (P) and nitrogen (N) can stimulate the growth of aquatic photosynthetic plant life (algae), which can decrease oxygen in the water and harm aquatic species (Lippiat, 2007).*

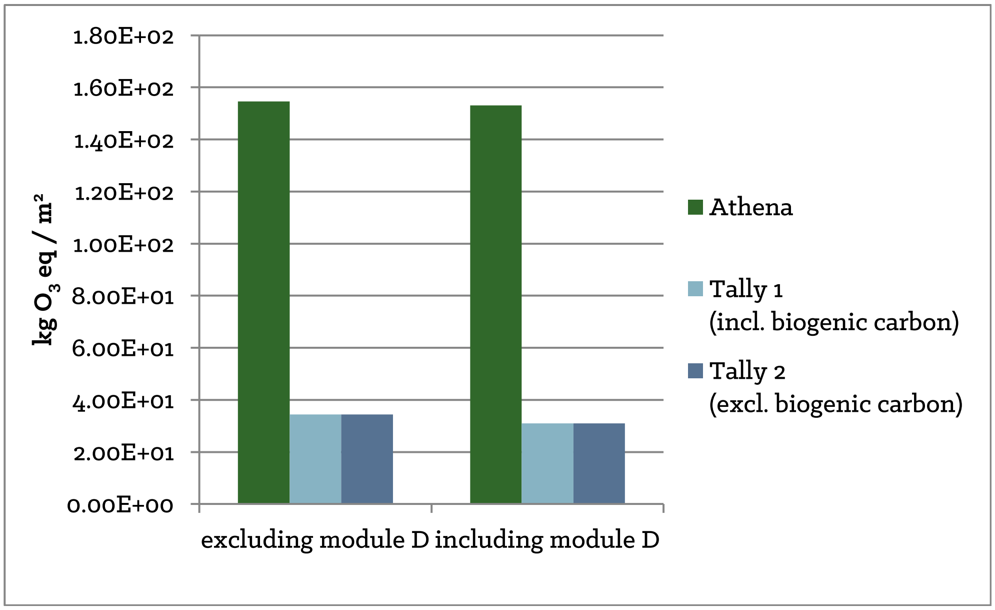


Figure 4.7 Smog Formation Potential (kg O_3 eq/m^2)

Photochemical smog *is the chemical reaction of sunlight, nitrogen oxides (NO_x) and volatile organic compounds (VOCs) in the atmosphere. Smog negatively impacts vegetation and causes human respiratory issues (Bare, 2012).*

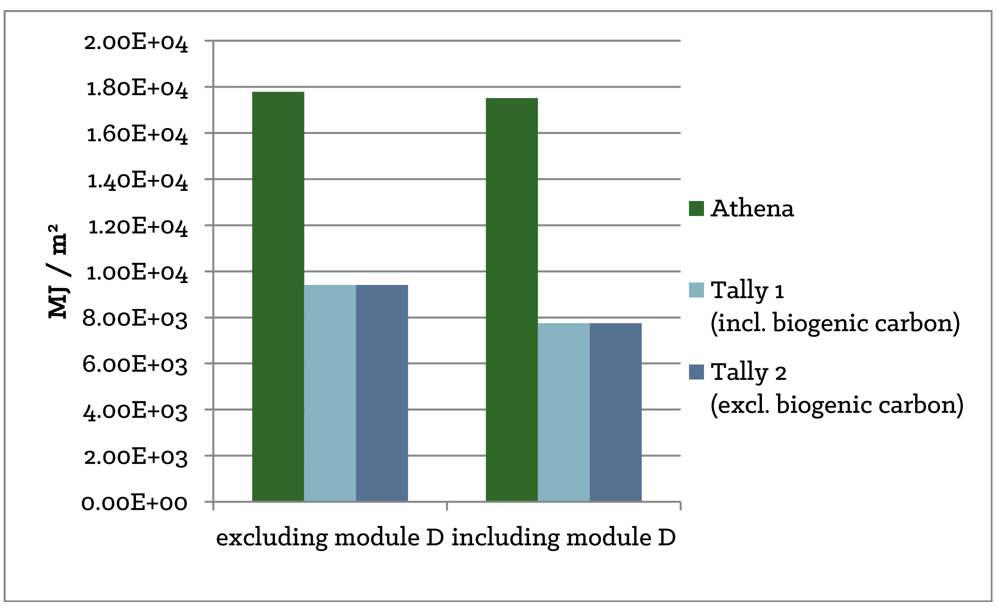


Figure 4.8 Primary Energy Demand (MJ/m^2)

Primary energy demand, *also known as "embodied energy" is a measure of the total primary energy needed to produce, transport, replace, and eventually demolish the building's materials. These numbers exclude operational energy (heating, cooling, etc.) and also exclude the energy expended by human labor.*

295% higher when including module D. The inclusion of module D has little effect on the impacts other than GWP, especially when compared to the difference from the chosen software tool. With regard to primary energy demand, which is the embodied energy of a building, Athena's impacts are 89% higher than Tally's when excluding module D, and 126% higher if including module D.

Lessons Learned & Opportunities

Compared to the several other WBLCAs in this series, the WBLCA of the CLTHouse had an expanded scope with a wider variety of materials and a larger surface-to-are ratio. The expanded scope logically resulted in larger environmental impacts per m^2. The wider variety of materials revealed the material limitations of the softwares; neither software had materials that exactly matched the sealants used in the CLT on this project.

Summary

The magnitude of WBLCA impacts including and excluding module D, as well as between Tally and Athena, is influenced by biogenic carbon calculation methods and end-of-life assumptions. The lowest calculated cradle-to-grave global warming potential is -936 kg CO_2 eq/m^2 , calculated in Athena and including module D. The largest calculated GWP is 557 kg CO_2 eq/m^2, which is calculated with Tally, excluding biogenic carbon and module D. The structure of this house is almost entirely wood, and thus contains a large amount of carbon stored within the structure. Some of this carbon may continue to be stored at the end of the material's life. In a landfill, various conditions influence decomposition rates for wood materials, but some of the carbon will nevertheless be permanently stored. Combined with potential module D benefits of burning wood for fuel (and avoiding fossil fuel use), these carbon storage and fossil fuel avoidance pathways are reflected in Athena's negative global warming potential.

The magnitude of other estimated environmental impacts beyond global warming potential was higher for Athena in all categories. Some impacts are sensitive to the inclusion or exclusion of module D, while others are not. Environmental impacts are not very sensitive to the inclusion or exclusion of biogenic carbon, other than global warming potential. For the final series conclusion and discussion, refer to the general summary at the end of the case study series.

CASE STUDY 5

Exterior photo of BC Passive House Factory © Ema Peter

WBLCA of BC PASSIVE HOUSE FACTORY

Building Description

BC Passive House Factory is a manufacturing facility located in Pemberton, British Columbia. Hemsworth Architecture designed the facility to showcase the client's commitment to sustainable and efficient wood-based construction. Glulam columns and beams on an insulated slab-on-grade concrete foundation form a large open floor space. Within the open plan, a small mezzanine provides office, conference and utility space. Three layer CLT exterior walls enclose the structure with a facade screen of 2 x 4 timber slats. A continuous line of clerestory windows bands the exterior for abundant natural light, with variable shading slats based on the wall's solar orientation. The flat roof is plywood supported by wood joists, topped with insulation and roof membrane layers.

Goals and Scope

This study contains multiple parallel WBLCA (whole building life cycle assessment) results using Tally® and Athena IE — one Tally result including biogenic carbon, one Tally result excluding biogenic carbon, and one result from Athena IE. The primary goal of this WBLCA is to determine the approximate environmental impacts of the building materials for an industrial facility with CLT components. A secondary goal is to understand how different software options may influence estimated environmental impacts, especially global warming potential. The scope of this WBLCA is the building's Revit model, which includes foundations, structure, enclosure, roof, stairs, interior partitions, doors, and windows. It includes basic finishes such as paint. It excludes sitework, concrete formwork, casework (cabinets/millwork), electrical, plumbing, and mechanical.

Completion
2014

Location
Pemberton,
British Columbia, Canada

Use
Industrial

Building Type
Combustible Permitted,
Heavy Timber Alternate

Building Area
16,146 sf (1500 sqm)

Design and Engineering
Hemsworth Architecture
Equilibrium Consulting, Inc
(Structural Engineering)

General Contracting
Dürfeld Constructors

Client
BC Passive House

CLT Manufacturer
Structurlam

The reference study period for this WBLCA, as well as the building's reference service life, is 75 years and is based on recommendations from ASTM E921 and ASHRAE 189.1 (Yang, 2018).

The primary **system boundary** for this WBLCA is cradle-to-grave, with the exclusion of B1 (Use), B6 (Operational Energy Usage), and B7 (Operational Water Usage). Case studies 1—3 excluded stage B impacts because the scope was limited to the structure of their respective buildings, due to Revit model divisions. This case study has an expanded scope that includes the enclosure and some finishes, which would be subject to replacement or refinishing during a 75 year lifespan. Thus, a limited module B scope has been included. The cradle-to-grave system boundary encompasses the environmental impacts associated with extraction of raw materials, manufacturing of materials, transportation to construction site, material repair/replacement, and material disposal. A cradle-to-cradle system boundary, which includes Module D: impacts beyond the system boundary, is also calculated and presented in this case study. This module assigns value to the consequential avoided fossil fuel emissions from end-of-life material decisions, such as the potential avoided fossil fuel emissions resulting from incinerating wood or from recycling materials. However, the impacts of this stage are less certain, as they depend upon consequences in other product systems (i.e. that less fossil fuel will be burned if wood is burned for fuel).

*"The **system boundary** determines which unit processes shall be included within the LCA. The selection of the system boundary shall be consistent with the goal of the study" (ISO, 2006)***.**

Methodology

For this case study, the software program Tally and the software program Athena IE generated multiple whole building life cycle assessment (WBLCA) reports. First, a Revit model was created based on the building's construction documents. Then, Revit materials were assigned specifications in the Autodesk Revit add-in Tally, outputting a pdf and excel report. With the Tally report's information, another WBLCA was put together in the Athena IE software.

A key difference between inputs is Athena's addition of construction waste factors (generally ranging from 0.01 to 0.05), which cannot be manually overridden, so Athena may have slightly higher mass calculations in many cases. However, in other cases, entering Tally's material volume into Athena results in a slightly lower material mass than Tally's value — presumably due to different material density assumptions.

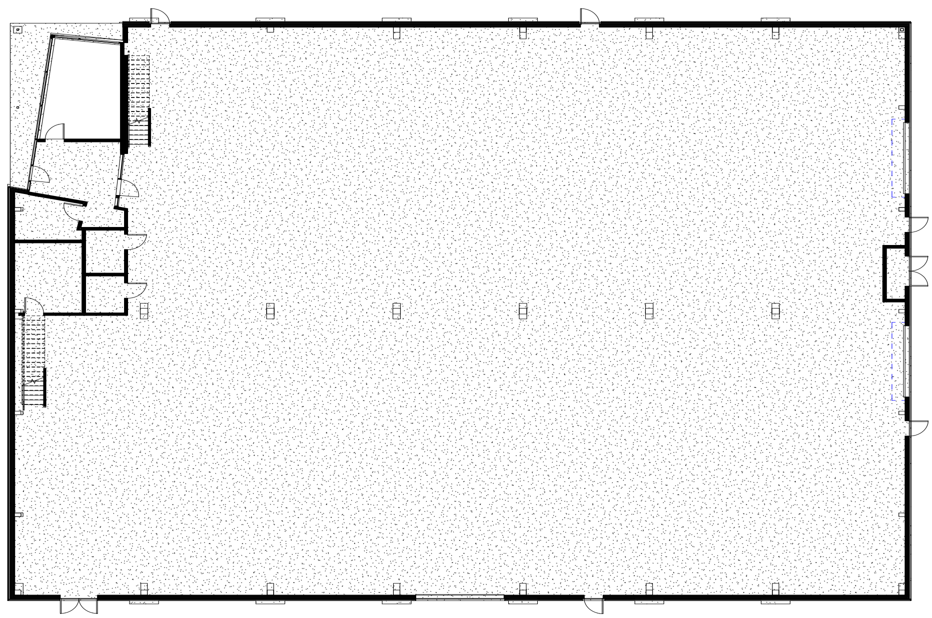


Figure 5.1 BC Passive House Factory floor plan (n.t.s.) © Hemsworth Architecture

Figure 5.2 interior of BC Passive House Factory © Ema Peter

Tally and Athena's differences of material calculation as well as other differences between the software (methodology and database sources) produces varying WBLCA results. Neither software consistently produced higher or lower results. To see the range of results, Tally and Athena's WBLCA data values are united in new excel graphs. For a more detailed methodology, refer to the case study series general methodology.

Assumptions

Both Athena and Tally have inherent assumptions and methods. Refer to the case study background for a description of key assumptions and differences. Material estimates are based on the Revit model created from the construction documents file. The Tally assessment and the Athena assessment use the same material quantity inputs.

For both Athena and Tally, a custom transportation distance of 432 km for glulam and CLT was used, which is the approximate distance from Structurlam, the manufacturer, to the construction site. In the Athena software, the building type was specified as "industrial" and the closest location was selected — Vancouver, British Columbia.

Results

BC Passive House Factory's environmental impacts are calculated for several impact categories: global warming potential, acidification potential, eutrophication potential, smog formation potential, and primary energy demand (embodied energy). Two software tools are used (Tally and Athena), and Tally generates two sets of impacts (including and excluding biogenic carbon). Each of the three reports cradle-to-grave impacts including and excluding module D, making a total of six calculation scenarios.

Discussion of Global Warming Potential

Estimates of global warming potential (see figure 5.3) ranges from 114 kg CO_2 eq/m^2 to 296 kg CO_2 eq/m^2. The lowest calculated global warming potential of 114 kg CO_2 eq/m^2 comes from Tally 1's calculation including biogenic carbon and excluding module D. Excluding module D, Athena's results (273kg CO_2 eq/m^2) are close to Tally's results that exclude biogenic carbon (296 kg CO_2 eq/m^2).

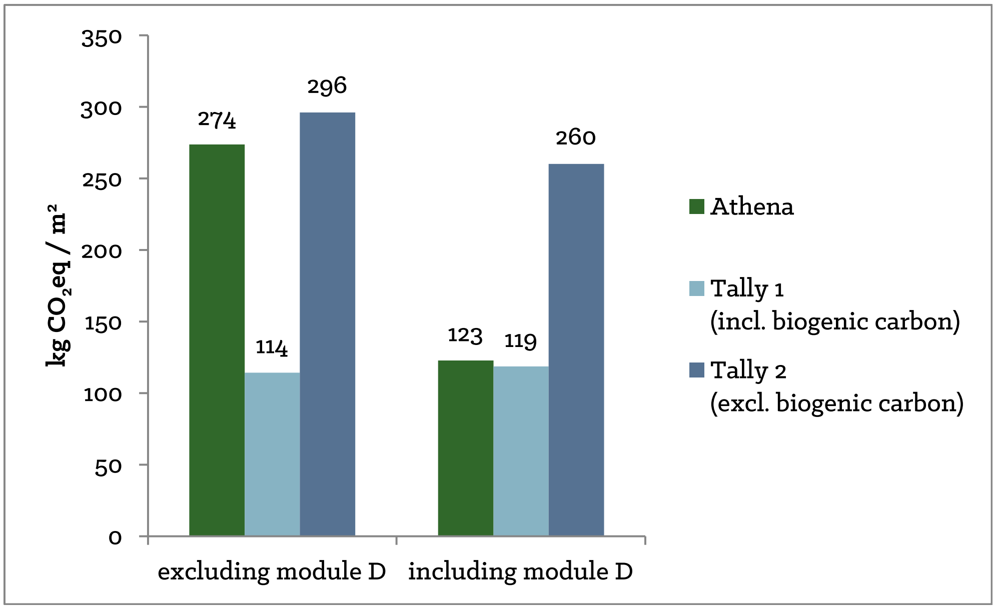


Figure 5.3 Global Warming Potential (kg CO_2 eq/m²)

Global warming potential *measures the sum of greenhouse gas emissions. This impact category encompasses the emissions of CO_2 as well as other greenhouse gases: CH_4, N_2O, SF_6, PFC and HFC, which are converted into the quantity of CO_2 that would lead to the equivalent amount of global warming potential (ISO, 2018, p. 4).*

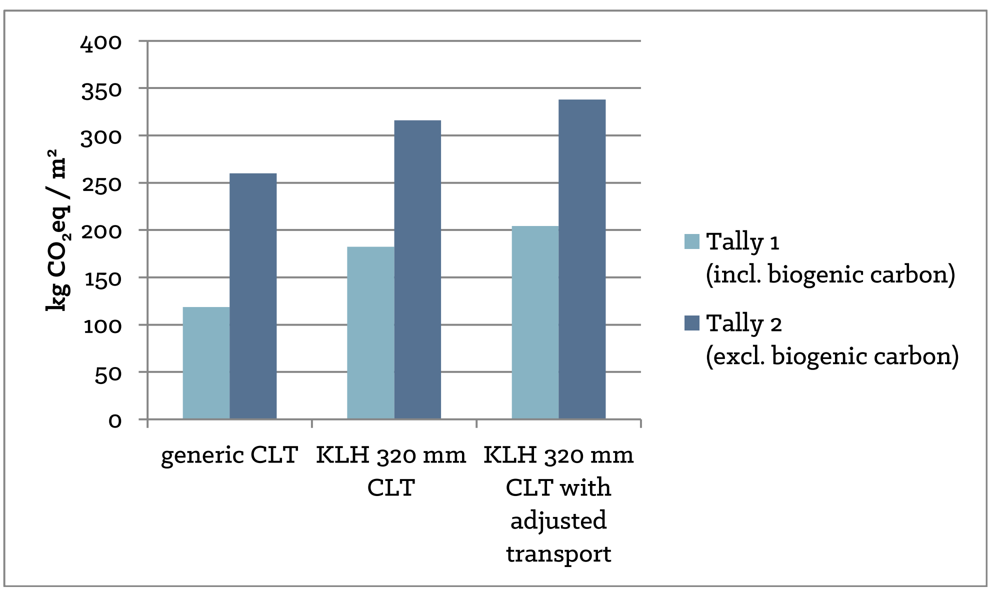


Figure 5.4 Sensitivity to CLT Manufacturer Selection and Transportation: Global Warming Potential (kg CO_2 eq/m²)

GWP in figure 4 includes life cycle stages A-D.

The largest GWP estimate is 296 kg CO_2 eq/m^2, which is calculated with Tally and excludes biogenic carbon and module D.

When comparing Tally's results excluding and including biogenic carbon, Tally 2 (excluding biogenic carbon) results in a GWP that is approximately 160% higher than Tally 1 (including biogenic carbon) if excluding module D. When including module D, Tally 2's results are 118% higher than Tally 1's.

Global Warming Potential: Sensitivity to CLT Manufacturer Choice & Transport Distance

Using Tally, a sensitivity analysis of the CLT panel's global warming potential shows how the GWP might change if a hypothetical alternate CLT manufacturer was selected and if transportation came from this alternate manufacturing location in Europe. In Tally, one can choose between a generic CLT material, which is based on adjusted North American glulam data, and a CLT material from the Austrian manufacturer KLH. For this sensitivity analysis, the GWP of the BC Passive House Factory is calculated for three CLT scenarios. The first assumes the generic CLT (which is analyzed in the rest of the case study), the second uses KLH's CLT (same transportation distance as scenario 1), and the third uses KLH's CLT and adds increased transportation due to KLH's Austrian manufacturing location. The second scenario increased the overall GWP by 54% when including biogenic carbon and by 21% when excluding biogenic carbon. The third scenario increased the overall GWP by 72% when including biogenic carbon and by 30% when excluding biogenic carbon. Refer to the introduction for more information on the comparative impacts

The adjusted transport distance covers approximate transportation from KLH's CLT factory in Teufenbach-Katsch, Austria to Pemberton, British Columbia:

~ 750 km truck
~ 6,520 km container ship
~ 5,000 km train

Discussion of other Environmental Impacts

For other environmental impacts Athena's impacts are higher for acidification potential, smog formation potential, and for primary energy demand (including module D only), but Tally's impacts are higher for eutrophication potential. For acidification, Athena's impacts are 34% higher than Tally's when excluding module D, and 45% higher when including module D. For eutrophication, Tally's impacts are approximately 59% higher than Athena's when excluding module D, and 57% higher when including module D. For smog formation potential, Athena's impacts are 51% higher than Tally's when excluding module D, and 63% higher when including module D. The inclusion of module D has little effect on the impacts other

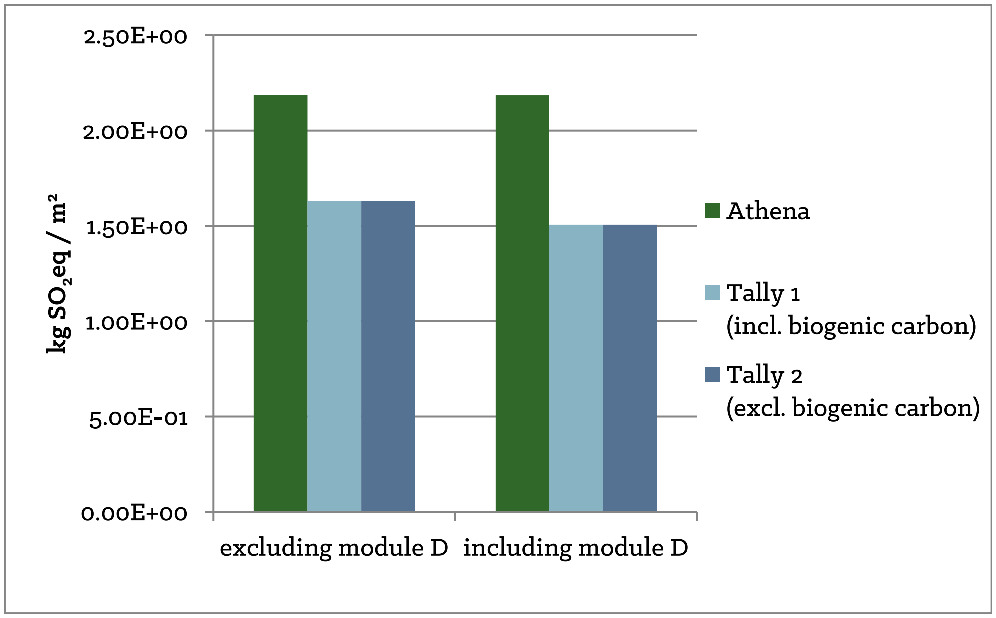


Figure 5.5 Acidification Potential (kg SO_2 eq/m²)

Acidification *occurs when an increased concentration of hydrogen ions (H+) alters the acidity of water and soil systems. Acidification and the resulting acid rain can harm ecosystems, plants, animals, buildings, and monuments (Bare, 2012).*

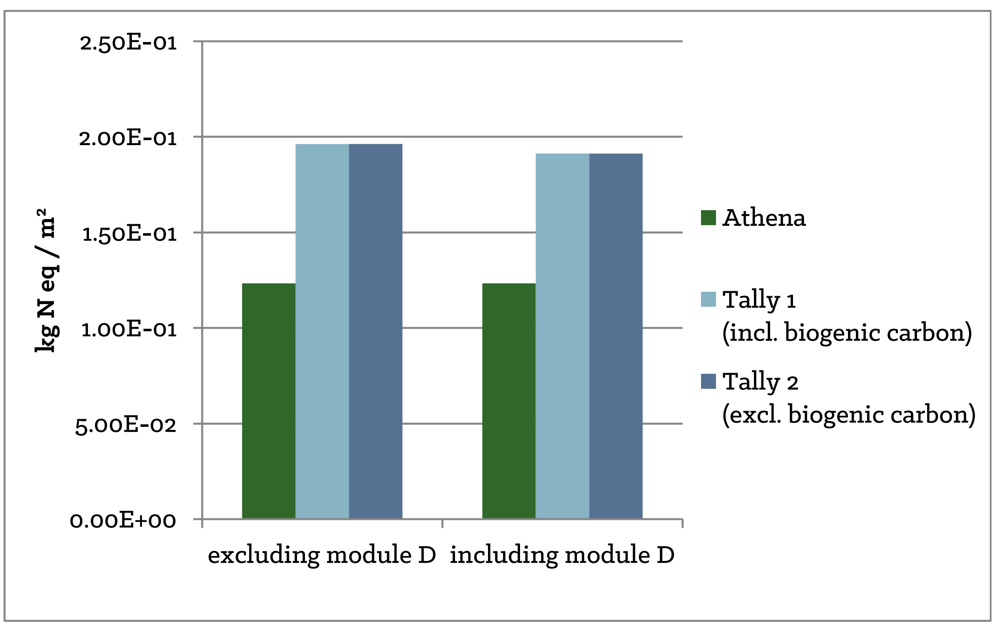


Figure 5.6 Eutrophication Potential (kg N eq/m²)

Eutrophication *refers to the addition of mineral nutrients to soil or water, damaging ecological diversity. In water, nutrients of phosphorus (P) and nitrogen (N) can stimulate the growth of aquatic photosynthetic plant life (algae), which can decrease oxygen in the water and harm aquatic species (Lippiat, 2007).*

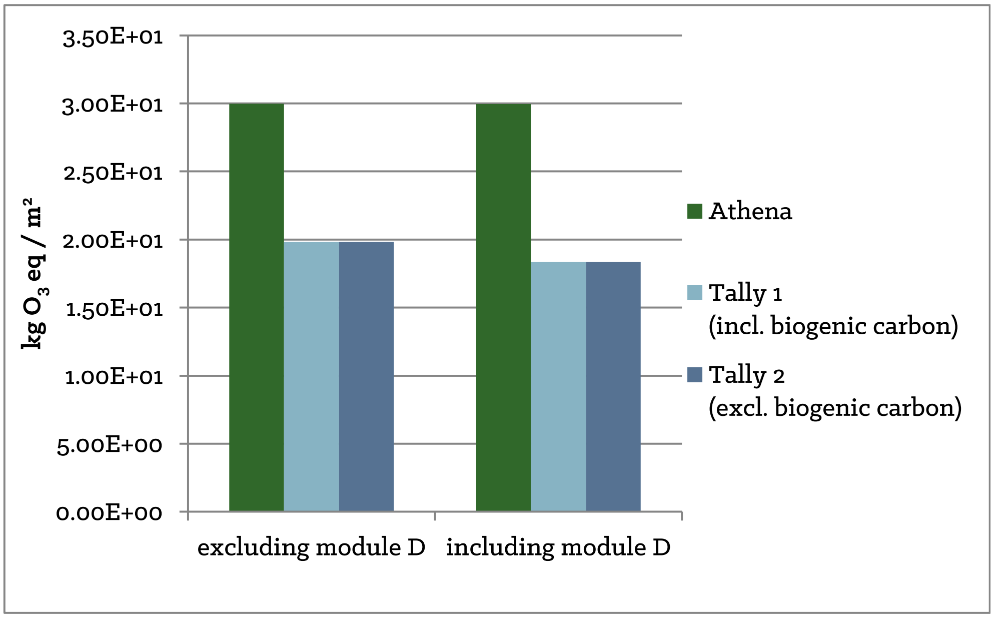


Figure 5.7 Smog Formation Potential (kg O_3 eq)

Photochemical smog *is the chemical reaction of sunlight, nitrogen oxides (NO_x) and volatile organic compounds (VOCs) in the atmosphere. Smog negatively impacts vegetation and causes human respiratory issues (Bare, 2012).*

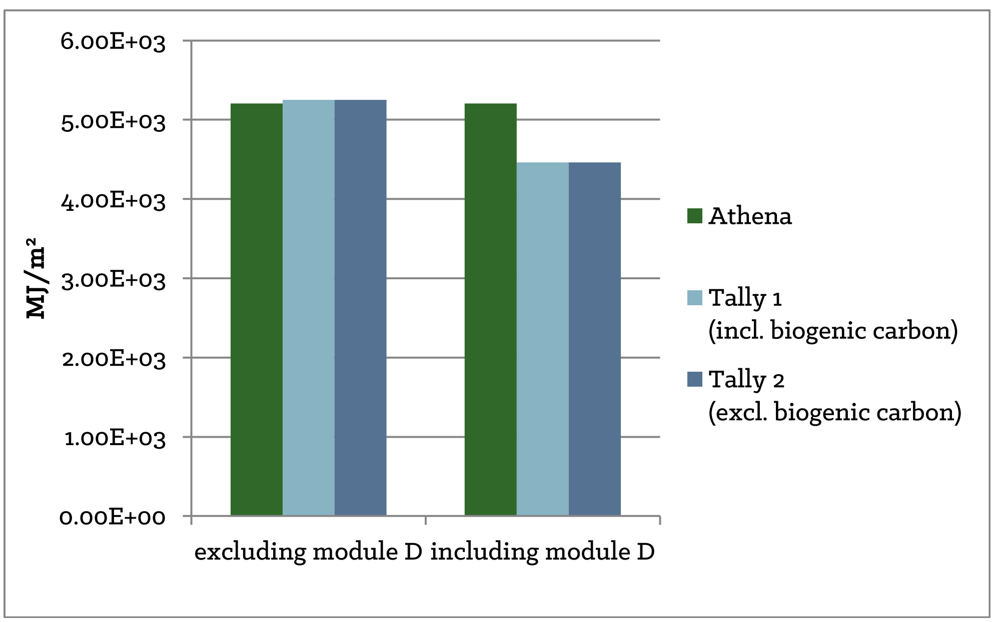


Figure 5.8 Primary Energy Demand (MJ/m^2)

Primary energy demand, *also known as "embodied energy" is a measure of the total primary energy needed to produce, transport, replace, and eventually demolish the building's materials. These numbers exclude operational energy (heating, cooling, etc.) and also exclude the energy expended by human labor.*

than GWP, especially when compared to the difference from the chosen software tool.

With regard to primary energy demand, which is the embodied energy of a building, Athena's energy demand is almost identical to Tally's when excluding module D, and 17% higher when including module D.

Lessons Learned & Opportunities

Compared to several other WBLCAs in this series, the WBLCA of the BC Passive House Factory had an expanded scope with a more materials. The wider variety of materials revealed that Athena does not have the same construction materials available as Tally. For more information on general lessons learned and opportunities, refer to the series conclusion.

Summary

The magnitude of WBLCA impacts including and excluding module D, as well as between Tally and Athena, is influenced by biogenic carbon calculation methods and end-of-life assumptions. The lowest calculated global warming potential is 114 kg CO_2 eq/m^2 , calculated in Athena and including module D. The largest calculated GWP is 296 kg CO_2 eq/m^2, which is calculated with Tally, excluding biogenic carbon and module D.

Athena's calculated environmental impacts are higher than Tally's in acidification potential and smog formation potential. For eutrophication potential, Tally's impacts are higher than Athena's. Some impacts are sensitive to the inclusion or exclusion of module D, while others are not. Other than global warming potential, environmental impacts did not change with the inclusion or exclusion of biogenic carbon.

Within Tally, global warming potential is also sensitive to the selection of CLT manufacturer and CLT transportation distance.

For the final series conclusion and discussion, refer to the general case study series summary.

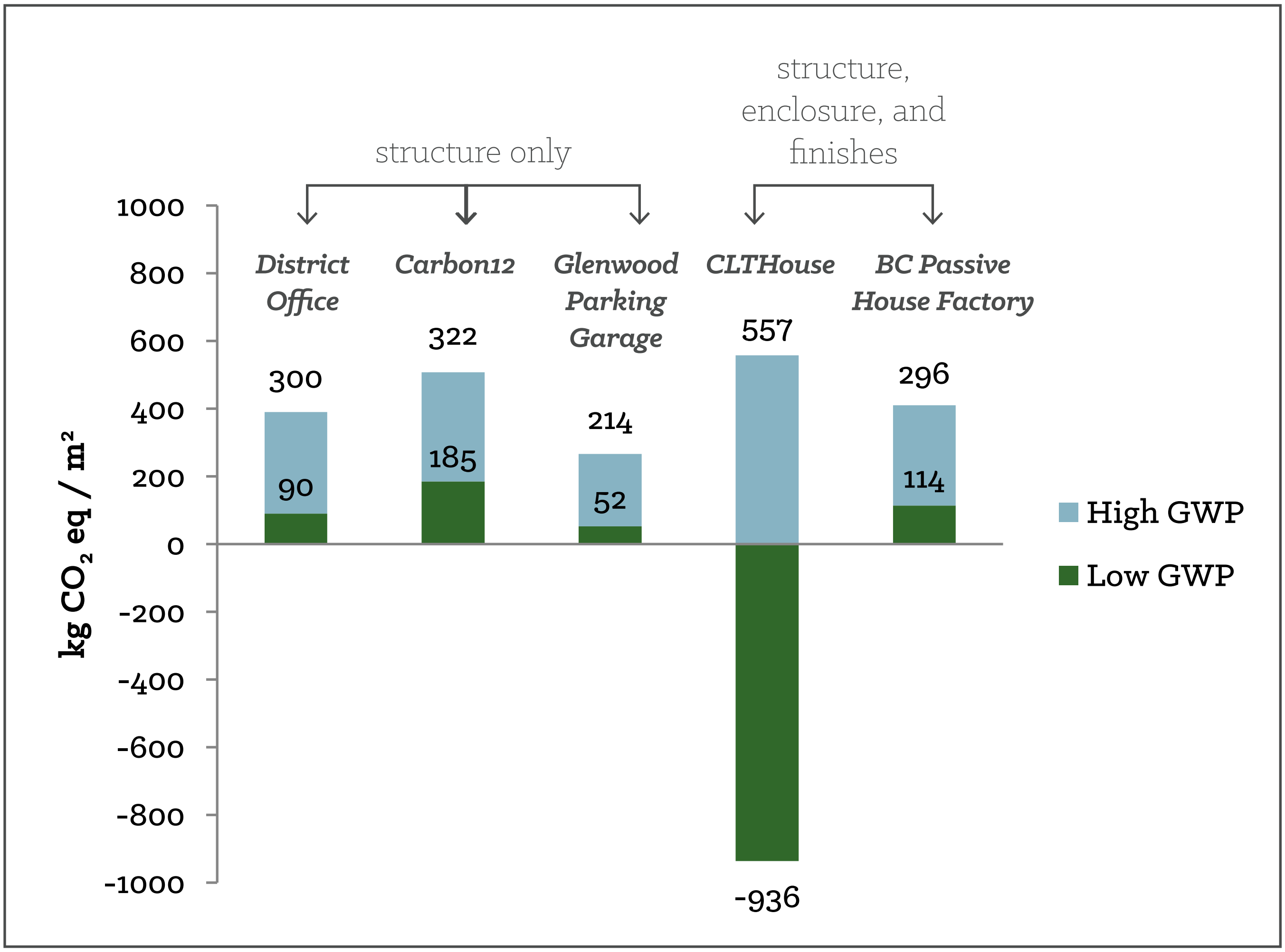


Figure 10 Global Warming Potential (kg CO_2 eq/m^2) of case studies

SERIES SUMMARY

The five case studies depict varying values of environmental impacts among WBLCA calculation scenarios using Tally and Athena IE. Neither software consistently results in higher estimations of environmental impacts, and both softwares are helpful tools for WBLCA practitioners. For an extended review of the softwares, refer to Appendix 2. Across the case studies, the global warming potential seems to be more sensitive to the specific calculation scenario than other environmental impacts. As evidenced by the GWP comparison of a single CLT wall in the introduction, CLT's impacts are heavily influenced by whether or not biogenic carbon is included and end-of-life assumptions — whether or not module D is included. Across the case studies, Tally's option to include or exclude biogenic carbon only affected the global warming potential, causing no change in any other environmental impact categories.

Refer to figure 10 for a comparison of the highest and lowest GWPs of each case study. Due to the large amount of CLT used, the smaller overall building size, and the inclusion of enclosure, roof, and finishes, the impacts of the CLTHouse are the highest and the lowest per square meter. Because of the large percentage of wood used, there is also a large negative GWP that reflects the carbon that remains stored in the materials at the end of life.

The conservative WBLCA for each case study excludes module D and biogenic carbon and may result in the overestimation of global warming potential for CLT and other buildings incorporating bio-based materials, such as wood. These values are the largest values in figure 9. Including module D and including biogenic carbon may result in the underestimation of global warming potential for CLT and other wood structures. Athena's results including module D are typically the lowest.

Biogenic Carbon

Compared to fossil fuel greenhouse gas emissions, biogenic carbon emissions present a greater complexity. The primary issues surrounding biogenic carbon's contribution to global warming potential are the timing of emissions and forest management sustainability practices.

For CLT, the timing of biogenic carbon emissions is spread throughout the product's life cycle. Biogenic carbon is sequestered in tree tissue throughout the growing process. When wood is harvested, the slash residue may decay in the forest or may be burned for bioenergy, emitting biogenic CO_2 and CH_4 (methane). In the CLT production process, waste wood is burned for energy at sawmills and the factory, emitting biogenic CO_2 and CH_4 as a product of combustion. The CLT product retains sequestered biogenic carbon during use, and at the end of its life cycle some biogenic carbon may be indefinitely stored, buried in a landfill. Typically, the biogenic carbon emissions burned for energy at the factory are assumed to be carbon neutral because it is assumed that growing replacement trees will reabsorb the carbon. This is a poor assumption; these biogenic carbon emissions generally still contribute to global warming potential because new trees cannot reabsorb the carbon dioxide as fast as it is emitted. Although this issue is widely acknowledged (Searchinger et al. 2009; Cherubini et al. 2011), alternative dynamic carbon models such as GWP_{bio} (Guest, Cherubini, & Strømman, 2013) or Time Zero Equivalent (Salazar & Bergman, 2013) have yet to penetrate mainstream WBLCA practice. These case studies do not account for the timing of biogenic carbon emissions because neither Tally or Athena IE support that capability.

Biogenic Carbon & Forest Management

When considering biogenic carbon, it is crucial to look beyond the product life cycle to the forest's carbon cycle. Theoretically, regrowing forests can absorb the carbon dioxide emitted during the previous harvest. However, where forests are not managed sustainably, or where there is land use change, the carbon storage of regrowth will not meet prior levels. Even changing the rotation period (intervals of time between harvests) could negatively impact the carbon storage potential of the forest. At this time forest management's effect on carbon storage of the forest (other than overt land use change) is not reflected at a product level like CLT, and thus is not reflected in WBLCAs. Forest management can play a role in climate change mitigation, despite its complexities. For this case study series, the buildings contain CLT from reputable North American manufacturers who source their wood from preexisting managed tree stands, so land use change was not a concern. For WBLCAs in areas of the world dealing with more deforestation, land use change may cause biogenic materials to be an environmentally detrimental choice.

Generally recognized ways to maximize the carbon benefits from a managed forest stand include extending buffer zones around waterways, lengthening rotation periods, (Diaz, Loreno, Ettl, & Davies, 2018, p. 3) improving the utilization of harvest, and shifting from short-lived to long-lived wood products (Smyth et al., 2014). However, leakage and product substitution effects must be considered at a global level to ensure that improving forest practices in one area does not lead to new deforestation elsewhere (Fain, Kittler, and Chowyuk, 2018).

Lessons Learned & Opportunities

This research uncovered the current limitations of calculating CLT impacts in WBLCA software. Only one specific CLT manufacturer has life cycle data included in the software, and no North American manufacturers have life cycle data in Tally or Athena IE. Adequate sealants and finish material options for CLT do not exist in Tally or Athena IE. Additionally, information about connection material average quantities and types is not well contained in Revit, Tally, or Athena IE. Future research could attempt to estimate these additional materials and investigate obstacles to their inclusion in the softwares.

The impacts of a single CLT wall were helpful to understand the base differences in Tally and Athena IE. This research could be extended to other wall materials such as steel and concrete. Additionally, in Athena IE, the use of different locations could be used to determine the potential regional effects.

The sensitivity of global warming potential to the influence of data sources and methodology reinforces the need to establish standard practices if embodied carbon and WBLCA will be used for government regulation or construction-related carbon taxes. With regard to biogenic carbon, specifics on how to account for biogenic carbon flows during the product life, as well as at the end of product life, will need to be included in standard practices. Whole building life cycle assessment standards such as EN15978 currently do not outline requirements for how to handle biogenic carbon or end-of-life behavior for materials, resulting in varying practices and inhibiting comparability between WBLCAs. Future standard WBLCA practice should also use biogenic carbon models that integrate timing of emissions and forest management information.

The environmental impacts of CLT present opportunities for improvement. Lesser-known and developed products of dowel-connected CLT and interlocking CLT do not use adhesives or metal fasteners. The transportation and production of adhesives can be a significant contributor to the environmental impacts of CLT, so CLT innovations that do not require adhesives may provide an opportunity to reduce these impacts.

Conclusion

The carbon sequestration of CLT and other wood materials may help reduce the embodied carbon of a building. In these case studies, the difference between Tally's option to include or exclude biogenic carbon shows the potential impact that biogenic carbon can have on reducing global warming potential at a material level, which contributes to the WBLCA level.

Bio-based building materials such as CLT and wood are not a panacea to climate change. Other materials can still be appropriate choices due to their thermal, mechanical, and aesthetic properties. Additionally, forest management carbon impacts and biogenic carbon accounting methods mean that the full carbon cycle impacts of wood materials may not be fully accounted for within an individual LCA or WBLCA.

Nevertheless, each material can be selected to reduce its embodied carbon impact. Architecture 2030's Carbon Smart Materials Palette identifies key attributes that contribute to a material's embodied carbon impact, and offers guidelines and options for emissions reductions during design and construction. This free online resource looks at whole building approaches to emissions reductions, as well as material-specific approaches for high-impact materials, such as concrete, steel, wood, and insulation) and "carbon-smart" materials.

Above all, sustainable design principles extend beyond a category of materials. Sourcing local materials, designing efficient structures, specifying higher recycled content percentages, and lengthening building lifespans are some strategies that should also be employed to reduce the environmental impact of building construction and use. WBLCAs can be a useful aid to achieve sustainability goals, but the limitations, uncertainties, and assumptions of WBLCAs must be noted.

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Disclaimer
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APPENDIX

Appendix 1: Tally Methodology: Including vs. Excluding Biogenic Carbon

Summary: Affects impacts of any bio-based, renewable materials such as: wood products, cellulose insulation, linoleum products, and strawboard. Excluding biogenic carbon is a more conservative approach.

Including Biogenic Carbon

1. Manufacturing Stages

Carbon content of bio-based material reduces GWP. If the material contains 1 kg CO_2 eq (as carbon), it will be counted as -1 kg CO_2 eq in the GWP.

Biogenic CO_2 and CH_4 (methane) emissions from burning biomass (i.e. wood waste burned for power at wood products factory) are included in GWP.

2. End-of-life Stages

Landfill C3-C4: includes biogenic CO_2 and CH_4 emissions from decaying wood, based on EPA WARM. 50% of biogenic carbon is permanently sequestered.

Landfill D: where landfill gas is combusted for energy, a credit is given based on the assumption of avoiding US average grid electricity and thermal energy from natural gas

Incineration C3-C4: 100% of biogenic carbon released as CO_2 based on carbon content of product.

Incineration D: credit for avoided US average grid electricity and thermal energy from natural gas

Recycling C3-4: includes any biogenic CO_2 emissions from processing

Recycling D: 100% of biogenic CO_2 uptake is passed on to the next life cycle so that user of recycled material can claim the environmental benefit of avoided production.

Excluding Biogenic Carbon

1. Manufacturing Stages

No credit to GWP for carbon content of bio-based material.

Biogenic CH_4 from burning biomass (i.e. wood waste burned for power at wood products factory) is still included. Biogenic CO_2 emissions are excluded.

2. End-of-life Stages

Landfill C3-C4: Biogenic CH_4 emitted in landfills is included (bigoenic CO_2 is excluded).

Landfill D: where landfill gas is combusted for energy, a credit is given based on the assumption of avoiding US average grid electricity and thermal energy from natural gas

Incineration C3-C4: Biogenic CO_2 is excluded, but biogenic CH_4 is included.

Incineration D: credit for avoided US average grid electricity and thermal energy from natural gas

Recycling C3-4: exludes any biogenic CO_2 emissions from processing

Recycling D: Credit for avoided production of material (and emissions) is given.

Appendix 2: Software Review: Tally and Athena IE

Tally

Tally's key strength is the depth of material-specific information provided in the report. Both the excel and pdf report provide an itemized list of every material and their respective impacts. This listing enables identification of emissions-intensive materials, and thus helps inform intelligent material comparisons during the design phase of projects. Tally's integration into Autodesk Revit makes it a powerful tool. If a company's Revit and Tally materials were well-integrated into their company templates, WBLCA could be swiftly generated (provided that good modeling practices are followed).

Despite having a fairly large selection of material options, there are still some absent material and finish options for CLT and other materials. For example, several material assemblies in Tally can include quantities of connectors, either defined by a default or custom quantity. However, in Tally, CLT does not have any option to specify connector type or quantity.

Athena IE

Athena IE produces a small chart of cumulative impacts, making it difficult to find carbon-intensive materials. Unlike Tally, the report does not include the life cycle inventory data sources for individual materials. However, Athena IE has a more comprehensive user guide than Tally, detailing general assumptions and providing how-to information.

Athena IE's user guide does not yet contain information on the data source for CLT, so that information was acquired through email communications.

Athena IE has a different set of material options than Tally and appears to have less specific manufacturer options. If there is a large percentage of custom concrete mix on a building, Athena IE may more accurately calculate the impacts, as there is a custom concrete mix tool. Tally has fewer options for concrete customization.

Both softwares require some learning and training to implement. The underlying assumptions of the softwares are not always stated in available resources, thus requiring additional investigation through software support. Luckily, both companies' support teams readily answer these and other software inquiries.

In some cases, Tally may be the preferable WBLCA software tool (cost-permitting), especially if the material data source will be a Revit file. Athena IE may be a preferable software tool if the material data source is bill of materials information from the construction phase or if Revit software is unavailable.

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