Mass Timber Comparative Life Cycle Assessment Series

Comparing the embodied carbon impacts and cost of mass timber buildings to functionally equivalent buildings

Introduction

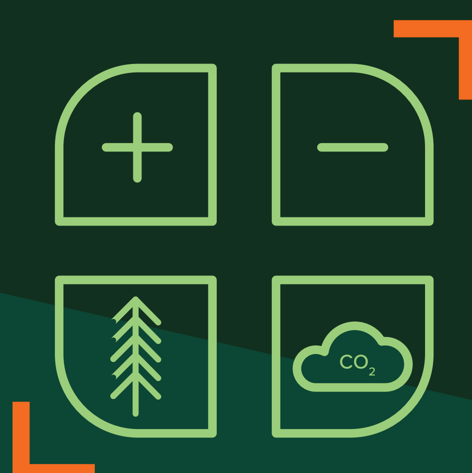

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Table of Contents

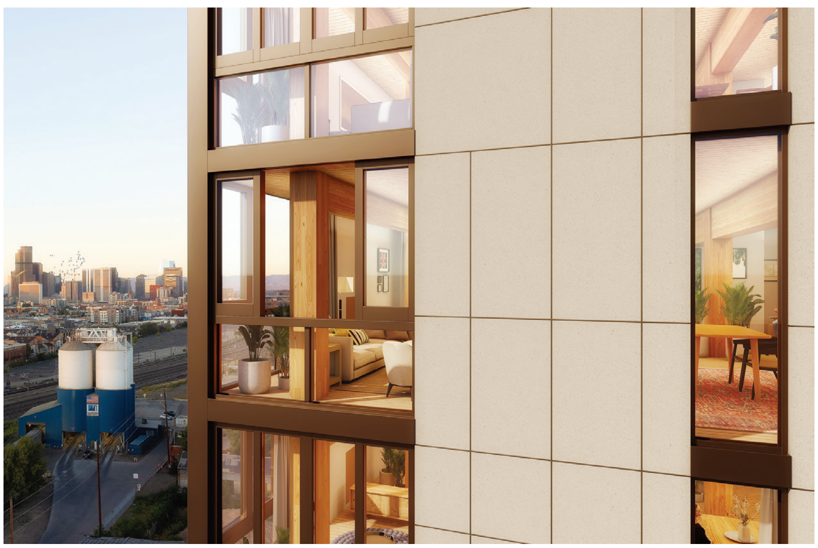
Introduction

In 2021, KL&A Engineers & Builders (KL&A), WoodWorks, and Think Wood published a comparative building study titled *Platte Fifteen Life Cycle Assessment*.[1] This study compares the global warming potential (GWP) and dollar cost of Platte Fifteen, a Type III-B over I-A mass timber retail and office building located in Denver, Colorado, to functionally equivalent[2] steel and concrete structural systems. It illustrates that the embodied carbon benefits and biogenic carbon storage potential of a mass timber structural system can be achieved with little dollar cost premium relative to traditional structural systems (Feitel et al., 2021).

The reception of that publication by design professionals and developers reinforces the perceived market desire for more comparative life cycle assessments (LCAs) and data. As such, to support the adoption, implementation, and success of mass timber buildings in North America as one of many embodied carbon reduction strategies, KL&A and WoodWorks have developed this *Mass Timber Comparative Life Cycle Assessment Series*.

The series is a compilation of comparative building studies based on designed reference buildings located in the United States. Some of the projects were fully constructed prior to the studies; others were in design. The reference buildings utilize mass timber structural systems and are compared to functionally equivalent structural systems such as steel or concrete in terms of embodied carbon (using whole building life cycle assessment, or WBLCA), dollar cost, and speed of construction. The authors have sought diversity in terms of geographic location, building use, size, construction type, and mass timber framing scheme to ensure that a variety of project types are represented.

The goal of this series is to illustrate the embodied carbon and economic implications of selecting mass timber structural systems through the individual LCA results. Studies include the embodied carbon impacts of materials and assemblies associated with structural systems, vertical and roof enclosures, fire protection, acoustic performance, and ceiling finishes to create a holistic comparison of construction types and structural systems.



Return to Form – Denver, CO
Katz Development, tres birds, KL&A Engineers & Builders / Nine stories of mass timber over three levels of concrete

This document is intended to serve as an introduction to the series and to define the general methodology, approach, and code compliance of the comparative design, LCA, and dollar cost analyses common to each building study. The authors have endeavored to be transparent in methodology, scope, and assumptions. Specific information and variations from the general methodology are discussed within each individual study.

Embodied Carbon and Its Measurement

The primary work of each building study is the quantification and comparison of the embodied carbon of functionally equivalent building systems. Embodied carbon represents the emissions associated with physical building materials, through their raw material extraction, production and manufacturing, transportation, installation, and end-of-life scenarios. It is quantified using LCA with the primary measurement expressed in terms of GWP in units of kilograms of carbon dioxide equivalent (kgCO_2eq). LCA results are typically presented in terms of GWP per gross floor area (kgCO_2eq/m^2 or kgCO_2eq/ft^2), which is the industry standard.

The built environment is responsible for roughly 42% of annual global greenhouse gas (GHG) emissions, 15% of which is embodied carbon and 27% is operational carbon as shown in Figure 1 (Architecture 2030, 2023). Unlike operational carbon, where impacts steadily accumulate over a building's lifetime, embodied carbon is both immediate and permanent. Embodied carbon represents nearly 100% of a building's emissions at construction completion and has more impact than operational emissions for the first 25 to 60 years of a building's life, depending on the type and efficiency of the building's mechanical and electrical systems (Architecture 2030, 2023; King, 2017; Carbon Leadership Forum, 2023). This is illustrated in Figure 2. As operational systems become more efficient, the relative impact of embodied carbon on the total building GWP impact becomes larger.

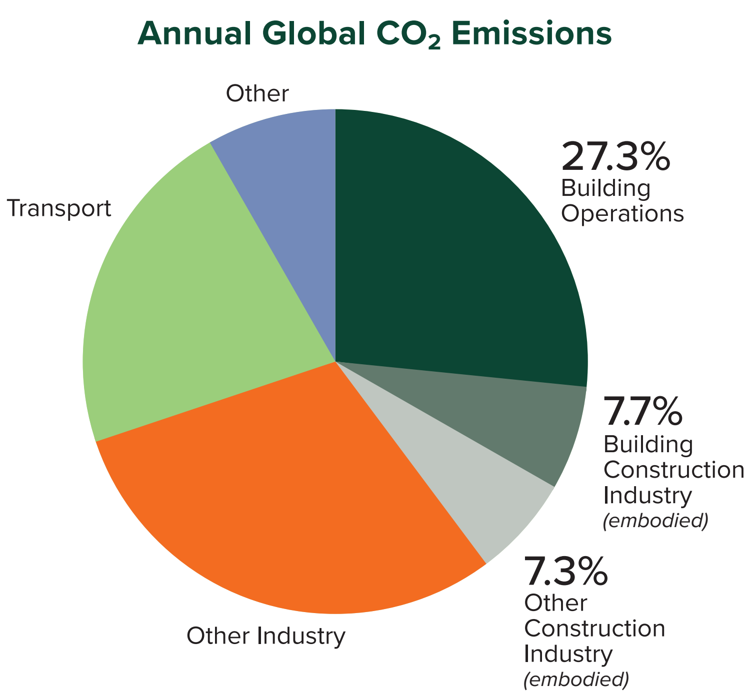


FIGURE 1: Embodied carbon emissions represent 15% of annual global CO_2 emissions.
Source: Architecture 2030, 2023

New Building Construction Carbon Emissions

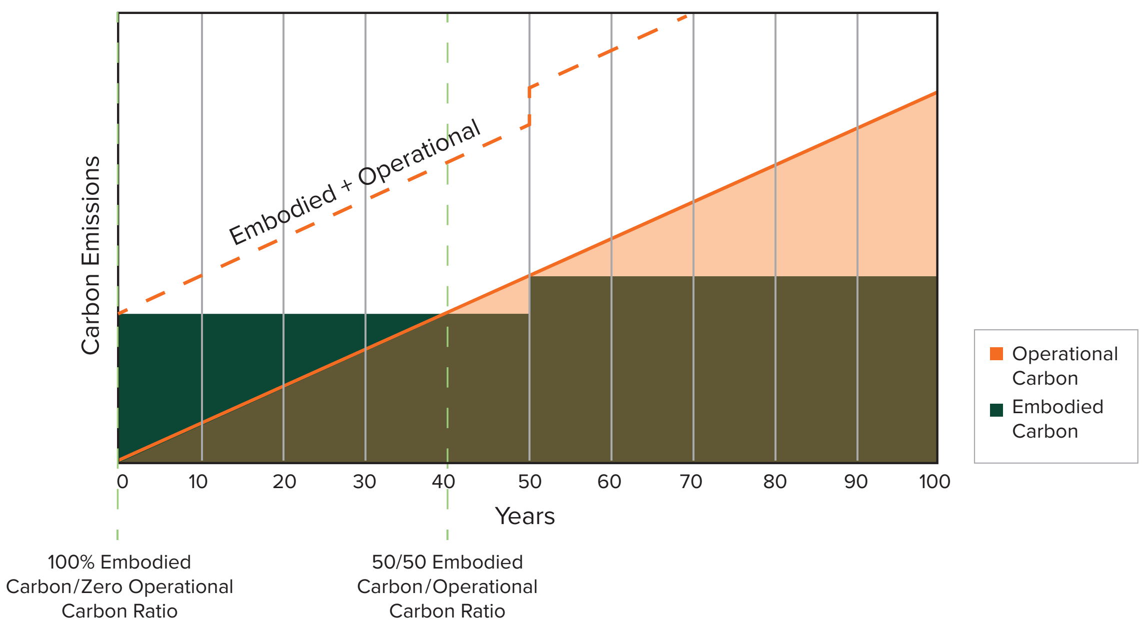


FIGURE 2: Relative contribution of embodied and operational carbon emissions over the life of a building, represented schematically

Source: Created with data from Architecture 2030, 2023; King, 2017; Carbon Leadership Forum, 2023

Building LCAs are founded on life cycle inventory (LCI), life cycle inventory assessment (LCIA), and environmental product declarations (EPDs). LCAs are used to quantify the associated emissions and various environmental impact categories of a building, system, assembly, product, or material, and consider life cycle stages such as cradle-to-gate, cradle-to-grave, or cradle-to-cradle. LCAs are estimates of GHG emissions and other environmental impacts based on current science, best practice, and governing requirements.

The environmental impact categories estimated in this comparative building study series are global warming potential (kgCO_2eq), acidification potential (kgSO_2eq), eutrophication potential (kgNeq), ozone depletion potential (kgCFC-11eq), smog formation potential (kgO_3eq), and renewable and nonrenewable energy demand (MJ). All impacts are reported in accordance with ISO 14044 (ISO, 2006) and ASTM E2921 (ASTM, 2022). The building studies focus on GWP because it is the impact factor that represents all GHG emissions, in proportion to their relative influence, which creates the conditions for global temperature rise. GHG emission impacts “can be reported with clarity, as they have a high degree of global agreement on reporting methods [...] The emissions of GHGs anywhere in the world results in the same global impact on climate change” (Simonen, 2014). The effects and risks of other emissions and environmental impacts are locally and regionally dependent, influencing their relative environmental importance. For example, the risks of acidification and eutrophication impacts vary depending on whether the region has exceeded, or is close to, its critical load.

Biogenic Carbon

Negative GWP values within LCAs and EPDs represent stored carbon or avoided impacts, typically in the form of renewable resources and material recycling or reuse. Substantial net negative impacts are typically only realized with biobased products, due to their natural ability to sequester carbon via photosynthesis.

Trees, like all plants, are part of the carbon cycle, as they continuously exchange carbon with the atmosphere through uptake during photosynthesis and release during decomposition or incineration. Referred to as biogenic carbon, this stored carbon is retained within the wood fibers throughout the lifespan of a wood product. The biogenic carbon content of wood is approximately 50% elemental carbon by dry mass of the wood fibers (Dovetail Partners, Inc., 2013).

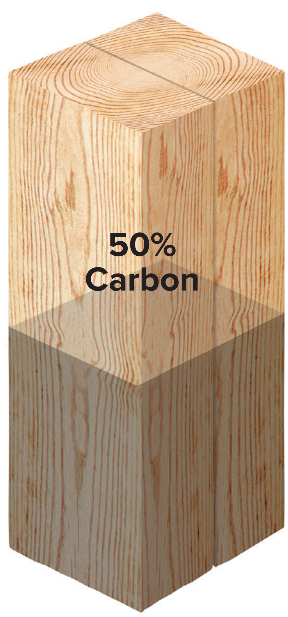


FIGURE 3: Wood contains approximately 50% elemental carbon by dry mass.

Per ISO 21930 (ISO, 2017) Section 7.2.11, wood material and products sourced from sustainably managed forests can assume a zero emissions impact for land use change (e.g., deforestation). This includes wood that is responsibly sourced and certified to standards developed by the Canadian Standards Association (CSA), Forest Stewardship Council (FSC), Sustainable Forestry Initiative (SFI), or other certification systems under the Programme for the Endorsement of Forest Certification International (PEFC), such as the American Tree Farm System (ATFS), or jurisdictions identified to have stable or increasing forest carbon stocks through national reporting per the United Nations Framework Convention on Climate Change (UNFCCC). All wood products sourced from North American forests meet these national reporting requirements[3] and are therefore permitted to consider the benefits of biogenic carbon within the products themselves.

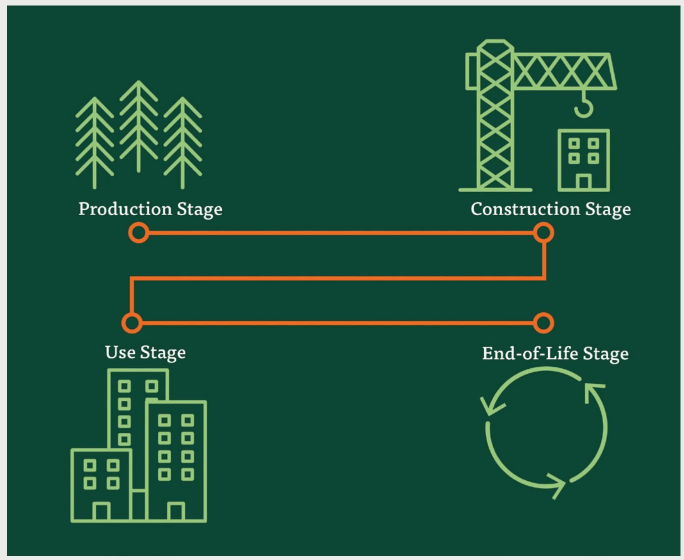
Per ISO 21930 Section 7.2.7, the biogenic carbon flow within wood sourced from sustainably managed forests as described above, may be characterized with a -1 $kgCO_2eq/kgCO_2$ when entering the product system (i.e., removal of carbon from the atmosphere) and a +1 $kgCO_2eq/kgCO_2$ when leaving the product system or when converted to emissions (i.e., decompostion or incineration).

The LCAs used in this series consider biogenic carbon flow using the -1/+1 characterization method. See the section, Life Cycle Assessment Data Methodology and Assumptions, for more information.

Learn to Account for Biogenic Carbon in Wood Buildings

This series of articles at woodworks.org is intended to help developers and design teams account for biogenic carbon in their wood building projects. It includes an overview followed by articles that examine accounting practices at each stage of a project's life cycle, the nuances of different LCA tools, long-term carbon storage and delayed emissions, and recommendations for reporting biogenic carbon in a way that aligns with international standards.

- *Calculating the Carbon Stored in Wood Products*
- *When to Include Biogenic Carbon in an LCA*
- *How to Include Biogenic Carbon in an LCA*
- *Biogenic Carbon Accounting in WBLCA Tools*
- *Long-Term Biogenic Carbon Storage*



Data Shows Forest Growth Continuing to Exceed Mass Timber Demand

North American forest carbon stock has been steadily increasing since reporting began in 1990—according to both the U.S. Environmental Protection Agency's *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 – 2021* and Canada's *National Inventory Report 1990 – 2021: Greenhouse Gas Sources and Sinks in Canada*. The U.S. Department of Agriculture's Forest Inventory and Analysis Program also reports that U.S. forest area has been stable for more than 100 years, and the volume of standing inventory on timberland has increased 60% within the past 60 years (Oswalt et al., 2018). Current forest harvest rates in the United States are 66% of inventory growth, even when considering fire losses. The highest forecasted demand for mass timber in 2035 translates to a potential increase of 17% over current harvest rates. Pairing the highest estimated mass timber demand with the lowest estimated forest inventory, forest growth in the United States will exceed harvest by 18% (Fernholz et al., 2022, Revised 2023).

Building Study Methodology and Assumptions

Each building study will compare the original mass timber reference building with one or more alternative structural systems. This section describes the design, LCA, and cost analysis methodology, assumptions, and noteworthy challenges.

Comparative Building and System Design

The alternative structural systems are typically designed by KL&A and are described in detail within each building study. In some cases, these systems were considered during the conceptual and schematic design phase of the project. The alternative architectural systems (enclosure, fire-rated assemblies, acoustic assemblies, and programmatic layout) are typically designed by the same Architect of Record as for the mass timber reference building.

The alternative building designs are functionally equivalent, meeting the same design criteria as the reference mass timber systems, meaning equivalent floor area, site orientation, occupancy, general programmatic layout, geographic location, load criteria, and performance requirements, in accordance with ISO 14044 Section 4.2.3.7 and ASTM E2921.

Because these case studies endeavor to create a holistic and fair material comparison of the structural systems, the comparative designs consider the nuances of the building's construction type and its effect on fire-rated assemblies, exposure, and material requirements. The construction type of the alternative systems may vary from that of the original mass timber reference building as appropriate.

Alternative structural designs:

- Are optimized for the materials and products used to reflect the realities of each system and ensure a fair comparison
- Account for effects of the building's weight on the foundation, gravity, and lateral systems
- Have the same enclosure systems, with consideration for the potential variation in construction type and fire-rating requirements

As examples of alternative design assumptions, consider a building's grid and floor-to-floor height. The column grid layout for concrete structural systems typically accommodates longer spans than mass timber systems; this geometric change represents common practice and works to the advantage of the concrete systems for material volume, embodied carbon, and dollar cost. Floor-to-floor heights may also differ for alternative systems. The floor thicknesses of mass timber, steel, and concrete assemblies vary due to the structural framing member depths and variances in acoustics, fire protection, and finish materials. In alternative designs, the floor elevations are adjusted to maintain a similar finish floor-to-ceiling height across the different structural systems. This floor elevation change captures total building height variations and any resulting effects on the exterior enclosure, interior walls, columns, and material volumes.

Comparative Life Cycle Assessment

The LCAs are performed by KL&A Team Carbon using Tally Life Cycle Assessment (TallyLCA) software, owned by Building Transparency, which is stated to conform to LCA standards ISO 14040-14044, ISO 21930:2017, ISO 21931:2010, EN 15804:2012, and EN 15978:2011.

The LCAs also conform to ASTM E2921 with the exception of ductwork, piping, wiring, and other miscellaneous system scope items, which are excluded. It is not yet typical for WBLCAs to include mechanical and electrical embodied carbon impacts, as there is very little embodied carbon data currently available and material quantities are typically unknown until construction is complete.

While the individual LCAs and embodied carbon data provided by TallyLCA are compliant with ISO, the comparative analysis and assertions of the LCA results are not compliant with Section 6.3 of ISO 14044: Critical review by panel of interested parties. The authors of this study believe the critical review requirements of ISO 14044 are aimed at the development and publication of EPD and LCIA data and are not intended for building LCAs relying on this data or LCA software; such review would be unduly burdensome for practicing designers, architects, engineers, and sustainability consultants comparing material and system alternatives. It is also understood that the critical review would have already been performed in the development of the background data, as the data is ISO compliant. Therefore, no third-party review is performed beyond that of the LCA practitioner, KL&A Team Carbon.

Return to Form – Denver, CO
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Life Cycle Assessment Material Scope

The typical component and material scope of the LCAs includes primary structure, vertical and horizontal enclosures, fire protection assemblies, acoustic assemblies, and interior ceiling finishes; as such, they are considered whole building life cycle assessments. Material quantities are based on the designed quantities and do not include final bill of materials or estimates for construction waste. Specific assemblies, materials, and products are discussed within each building study along with any variations from this scope description.

The primary structure includes below-grade substructure (foundations) and above-grade superstructure elements (gravity system: floors, roofs, beams, columns, bearing walls; lateral system; slab-on-grade). Steel reinforcement within concrete elements is included. Connections and accessory structural elements such as miscellaneous metals are typically excluded from the LCAs in this series.

The vertical enclosure includes the exterior finish, glass and curtain wall systems, waterproofing, insulation, wall framing, and fire-protection materials such as gypsum board. The horizontal enclosure includes the exterior finish, waterproofing, insulation, framing, fire-protection materials, and acoustic materials.

Including materials necessary to achieve fire-resistance ratings (FRRs) in the LCA scope is particularly important. Some code-designated construction types allow combustible materials in the primary structure, while others do not. In concrete structures, the FRR is typically achieved with the inherent properties of the structural concrete itself, combined with steel reinforcement cover requirements. Similarly, many mass timber systems rely on the inherent fire resistance of the wood itself by accounting for the necessary char depth to achieve the required FRR as part of the member structural design and sizing. Depending on the building construction type, some mass timber systems may require noncombustible encapsulation of wood materials (typically with gypsum board) or a combination of exposed and covered surfaces. Fire-rated steel systems typically rely on the use of gypsum board coverings, spray-applied cementitious fireproofing, or intumescent paint. All these scenarios affect the embodied carbon, dollar cost, speed of construction, and aesthetic appearance of the system. Therefore, each alternate system is assigned an appropriate construction type and the resulting exterior wall, roof, floor, and interior fire-rated wall assemblies are included within the scope of the design, LCA, and dollar cost estimates.

Exterior finish and ceiling finishes are included within the LCAs. All other architectural finishes (floor finishes, interior wall finishes, paints, stains, sealers, etc.) are excluded. Ceiling finishes may serve as fire protection (gypsum board), aesthetic coverings, and in some cases acoustic barriers. The purpose of including ceiling finishes within the LCAs is to quantify the potential embodied carbon benefits of mass timber's biophilic aesthetic and inherent fire resistance when compared to other structural systems and materials. In general, the alternative systems assume the same ceiling finishes and exposed structure surface areas as the reference mass timber building unless exposed structure is atypical for a given structural system within the reference building's market. The intention is to avoid assumptions regarding aesthetic preferences in alternative architectural systems.

Other LCA scope exclusions are site work, civil, landscape, mechanical, electrical, plumbing, and all interior furnishings.

Life Cycle Assessment System Boundary

ISO 21930 defines the four stages of the life cycle as the Production Stage, Construction Stage, Use Stage, and End-of-Life Stage as shown in Figure 4.

The LCA system boundary for this series is cradle-to-grave (A-C, plus D), inclusive of Modules A1-A3, A4, B2-B5, C2-C4, and Module D.

The Production Stage (A1-A3), termed cradle-to-gate, typically has the largest embodied carbon impact when considering all life cycle stages of a material or building.

The Transportation Module (A4) is included for all materials and components. In most cases, A4 impacts utilize TallyLCA's default assumptions, which are based on U.S. industry averages. Steel and concrete are typically sourced locally or regionally. The mass timber A4 metrics are altered to consider the actual transportation distances and methods if the project's supplier was known at the time of the LCA analysis. Transportation assumptions and impacts are discussed within each building study.

Life Cycle Stages:
Cradle-to-Grave + Module D

Production			Construction		Use							End-of-Life				Module D		
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D1	D2	D3
Raw Material Supply	Transportation	Manufacturing	Transportation	Construction/Installation	Use	Maintenance	Repair	Replacement	Refurbishment	Operational Energy Use	Operational Water Use	Deconstruction/Demolition	Transportation	Waste Processing	Disposal	Reuse	Recycling	Energy Recovery

Note that the stages and information modules shown here deviate slightly from the naming convention used in ISO 21930. However, this series generally uses terminology consistent with ISO 21930.

FIGURE 4: LCA life cycle stages; scope inclusions in light green

The Construction/Installation (A5) and Deconstruction/Demolition (C1) Modules are excluded from the LCAs. TallyLCA does not provide default or average LCI data and impacts for A5 or C1, and construction/deconstruction impact data is lacking within the industry. Some LCA practitioners apply a percentage increase or formulaic ratio to the A1-A4 impacts to consider A5 or C1. Although it is ideal to consider all aspects of the building's life cycle, simple ratios do not consider the nuances of the material weights, installation methods, prefabrication potential, typical waste rates, labor intensity, and contractor means and methods preferences. For this series, it was determined that the addition of A5 and C1 impacts would not add clarity or accuracy to the results, and would dilute the comparative analysis. Speed of construction is discussed qualitatively and is considered in the dollar cost analysis of each comparative building study.

The Use (B1), Operational Energy Use (B6), and Operational Water Use (B7) Modules are also excluded from the LCAs. Maintenance, Repair, Replacement, and Refurbishment (B2-B5) are included, although they typically have a minor impact. The majority of materials and components are considered to have an equivalent service life to the building, and therefore have no impact at Stage B. Glass, windows, and roof finishes are assumed to have a 30 to 40-year life cycle, and therefore do have Stage B impacts. The specific life cycle assumptions are discussed within each LCA study, along with any variations from this typical description.

End-of-Life Modules (C2-C4) are included for all materials and components. End-of-life mix allocation assumptions are described in the section, Life Cycle Assessment End-of-Life Methodology.

Module D benefits and impacts technically belong to the next system boundary, such as a building or product that reuses materials from the original studied building. As TallyLCA does not allow the exclusion or proper separation of benefits and impacts that occur beyond the system boundary (reuse, recycling, energy recovery) from the analysis, Module D is included and reported within the LCAs. Eliminating Module D from the LCA results is not a straightforward modification to the system boundary as the impacts and credits reported in Stage C and Module D are not readily disaggregated. Stated differently, if Module D results were subtracted from the study, the full end-of-life impacts would not be accounted for in the LCA results.

The service life of the building, representing the reference study period (RSP), is 75 years unless noted otherwise, which is compliant with ASTM E2921. It is common for RSPs to be set to 60 years, as this is accepted by the Leadership in Energy and Environmental Design (LEED), Building Research Establishment Environmental Assessment Method (BREEAM), and International Living Future Institute (ILFI) green building certification programs. The authors of this comparative building study series chose to align with ASTM E2921 in lieu of a clear industry standard. The effects of a 75-year RSP versus 60-year RSP in the context of these studies is insignificant. For the majority of materials, service life will match that of the building's life expectancy and will therefore have zero consequence on the total embodied carbon impact. Some materials, such as windows and roof finishes, are considered to have a shorter service life, such as 40 years. TallyLCA's methodology is to consider one replacement impact of these components at Modules B2-B5, at 40 years, versus scaled impacts (75 years/40 years = 1.875). A second replacement impact would be considered at 80 years and is therefore outside the system boundary and not applicable to the 75-year RSP or 60-year RSP scenario.

Life Cycle Assessment Data Methodology and Assumptions

The LCA results presented in this series are limited by the specific EPDs and LCI data available within the TallyLCA database, as well as the software's Stage C and Module D end-of-life mix allocation. (See the Appendix for TallyLCA's stated methodology.) TallyLCA's database is a custom LCA database "that combines material attributes, assembly details, and architectural specifications with environmental impact data resulting from the collaboration between KieranTimberlake Innovations and thinkstep. LCA modeling was conducted in GaBi 8.5 using GaBi 2018 databases and in accordance with GaBi databases and modeling principals" (Tally, 2023). The LCI data is primarily based on North American average values. End-of-life mix allocation and scenarios are based on U.S. average rates.

It is standard for EPDs to report only Modules A1-A3. When TallyLCA utilizes an industry or product EPD, it provides supplementary data for A1-A3 and additional data for the remaining modules available within the GaBi database. If available within TallyLCA, industry-average EPD data is the preferred data selection for the materials and components within these LCAs. The major structural materials included in this series—mass timber, steel, and concrete—are all reported using industry-average EPDs. Specific EPD and LCI data selections are provided in each LCA study.

TallyLCA conforms to the U.S. EPA Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts (TRACI) characterization scheme for reporting the different environmental impacts, which is the North American standard.

As noted, these building studies focus primarily on GWP (kgCO_2eq), although all impact factors calculated are reported in accordance with ISO 14044 and ASTM E2921 (acidification potential, eutrophication potential, ozone depletion potential, smog formation potential, renewable and nonrenewable energy demand).

TallyLCA's cut-off criteria states that "materials are included up to a 1% cut-off factor by mass except for known materials that have high environmental impacts at low levels. In these cases, a 1% cut-off was implemented by impact" (Tally, 2023). The structural and architectural materials included in the stated LCA scope use rigorous material volumes based on the design documentation.

TallyLCA does not consider the effects of concrete carbonation and it is therefore excluded from the LCAs.

Biogenic carbon is included in the LCAs. As noted, North American wood products meet ISO 21930 Section 7.2.11's sustainable sourcing definition, and it is therefore permitted to consider the wood products' natural ability to store carbon. TallyLCA includes biogenic carbon flow as part of the reported GWP using an attributional and static -1/+1 characterization method, per ISO 21930 Section 7.2.7. Within the LCAs, the biogenic carbon enters the system at Stage A, at which time it is roughly 50% elemental carbon by dry mass of the wood fibers, based on the wood volume within the assessment (Figure 5).

Value of Biogenic Carbon at Stage A in TallyLCA

The value of biogenic carbon when it enters the system at the A1-A3 Stage in TallyLCA is comparable to an EPD's reported biogenic carbon leaving the manufacturer at Module A3 and is calculated using the formula below.

$GWP_{\text{Biogenic Carbon}}$ [kgCO_2eq/m^3] = 0.5 [kgC/kg] x (Dry Weight of Wood Products) [kg/m^3] x 44/12 [kgCO_2eq/kgC]

For more information, see the WoodWorks article, *Calculating the Carbon Stored in Wood Products*.

The biogenic carbon is stored within the wood products until the building's end-of-life, when it is demolished or deconstructed, and the wood products are buried in a landfill, burned for energy, or recycled (Stage C and Module D). TallyLCA's methodology and assumptions result in 31.75% permanent storage of the biogenic carbon, which is conservative when compared to Athena Impact Estimator's assumption of 64% permanent storage (WoodWorks, 2023). Mass timber end-of-life assumptions are further detailed in the section, Life Cycle Assessment End-of-Life Methodology.

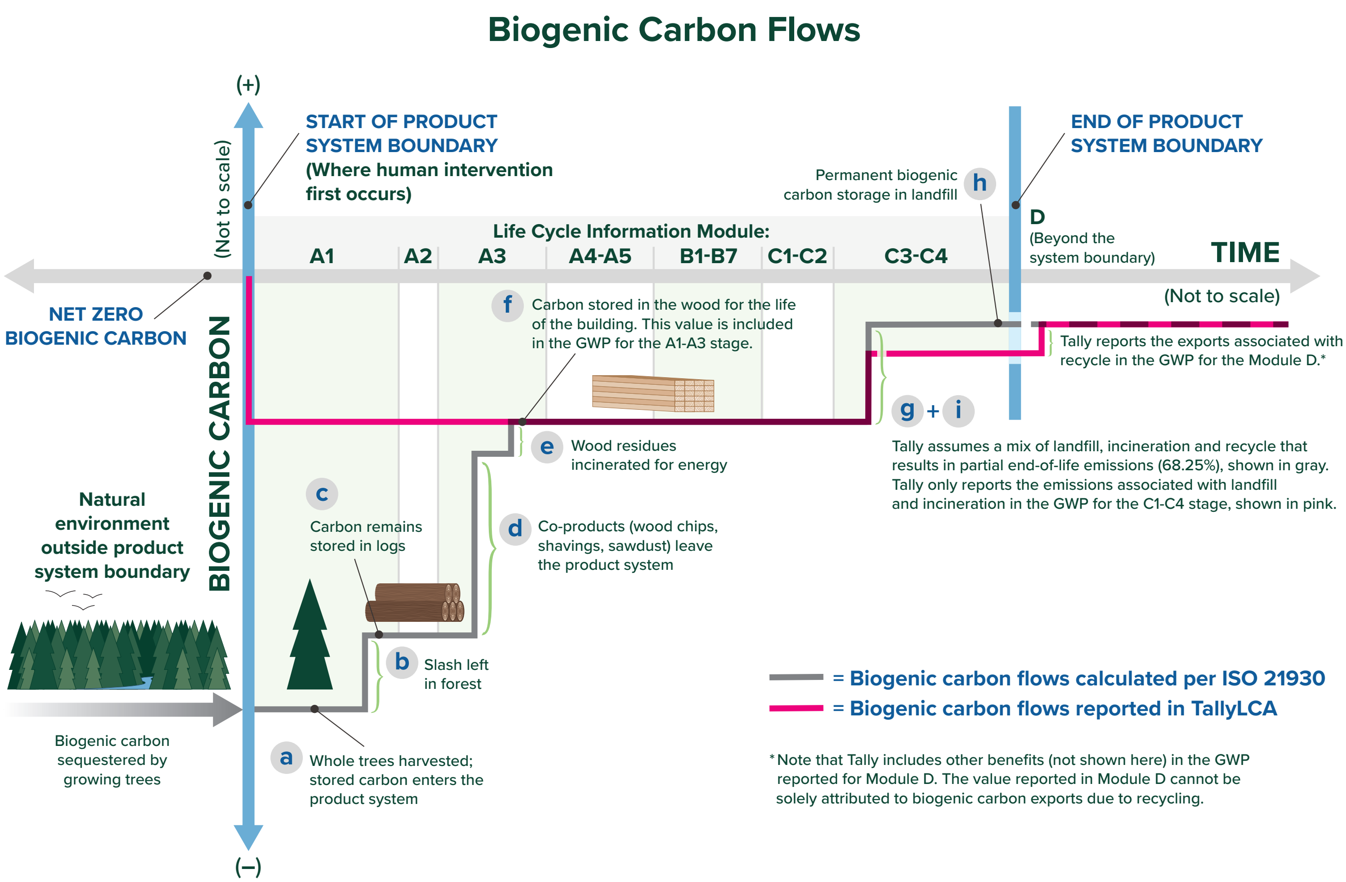

FIGURE 5: Biogenic carbon accounting in TallyLCA
Source: Biogenic Carbon Accounting in WBLCA Tools, WoodWorks

Life Cycle Assessment Data Uncertainty and Limitations

As building product EPDs and LCI data become more readily available and the standardization of material, product, and building LCAs evolves, building LCA results and comparative studies will become more accessible and influential. Until then, currently available data is sufficient to reasonably inform system and product selection, and identify significant “hot spots” and reduction opportunities within the assessment.

Due to the complex nature of environmental impact analysis, the relative scarcity of manufacturer product-specific EPDs, and the need for more comparable data across system and product types, some uncertainty in the quantification of the building impact is acknowledged. While the term “uncertainty” may be unsettling, the primary objective of executing a WBLCA is to guide immediate action to reduce emissions associated with design and construction. The data, methodology, and standard of practice will progress through collective analyses, and as more aspects of material impacts and scenarios are explored and nuances better understood. The authors of this comparative LCA series endeavor to be transparent in methodology, assumptions, and scope, to identify possible pathways for immediate embodied carbon reductions in new construction.

Although this study is not intended to be an exploration of the advantages and disadvantages of the TallyLCA software, it is important to understand its limitations and potential implications to the LCA results, as is the case for any LCA tool. TallyLCA is owned by Building Transparency, which also owns and operates EC3 and TallyCAT. It is one of the main LCA programs used by LCA and design practitioners in the North American building industry. TallyLCA is KL&A Team Carbon’s preferred cradle-to-grave LCA tool because the workflow is most seamless with standard structural engineering practices and processes. TallyLCA is a plug-in program to Autodesk Revit, which creates the basis and management of the major material quantities used in the LCA. However, the TallyLCA database is not regularly updated, resulting in a number of expired EPDs and outdated LCI data. The authors have endeavored to identify instances that impact the LCA results.

Below is a list and discussion of EPD and LCI data used for the major material categories within the *Mass Timber Comparative Life Cycle Assessment Series*. For references, see Environmental Product Declaration Sources.

- **Cast-in-Place Concrete**
  - *Concrete Industry-Average EPD* (2019), National Ready Mix Concrete Association (NRMCA)
  - TallyLCA does not explicitly reference the EPD version used, but concrete A1-A3 GWP impacts within the tool have remained consistent over the last three years and are assumed to be referencing the NRMCA *Concrete Industry-Average EPD* issued on 11/16/2019 and expiring 11/16/2024, and not the more current version issued on 1/3/2022. The newer version has a roughly 10% GWP (A1-A3) impact reduction compared to the 2019 EPD. This reduction in GWP data across EPDs disadvantages the concrete systems most, although significant concrete volume occurs within most building systems.
- **Concrete Reinforcing Steel (Mild Steel Reinforcing)**
  - *Concrete Reinforcing Steel Manufacturer-Specific EPD* (2015), Commercial Metals Company (CMC)
  - Expired 9/1/2020
  - The current *Concrete Reinforcing Steel Industry-Average EPD* (2022), published by the Concrete Reinforcing Steel Institute (CRSI), is not available in Tally. It has a 0.5% GWP (A1-A3) impact increase compared to the expired CMC 2015 EPD.

- **Precast Concrete**
  - No precast concrete data set is available within TallyLCA. The cast-in-place concrete data noted above is used as a proxy.
  - This data selection likely favors the concrete system LCAs because the data underestimates the GWP impact by 33% when compared to the current *Canadian Precast/Prestressed Concrete Institute's and Precast/Prestressed Concrete Institute's North American Industry-Average EPD* (2019).
  - This data selection misrepresents the LCA Stage associated with some GWP impacts. For example, embodied carbon associated with the pouring, curing, and formwork of the precast product occurs in Module A3 (Production Stage); however, for a cast-in-place concrete product this impact occurs in Module A5 (Construction Stage). Module A5 is excluded from the scope of this study series.
- **Concrete Masonry Unit (CMU), Hollow-Core**
  - Generic LCI data set by TallyLCA
  - Expiration unknown
  - No U.S. industry-average EPD exists; however, there is a Canadian industry-average EPD, *Canadian Concrete Masonry Producers Association EPD* (2022).
  - Numerous manufacturers in North America have published EPDs.
- **Mortar**
  - Generic LCI data sets for various mortar types by TallyLCA
  - Expiration unknown
  - No North American industry-average EPD exists.
  - Numerous manufacturers in North America have published EPDs.
- **Grout**
  - Generic LCI data set by TallyLCA termed "thickset mortar"
  - Expiration unknown
  - No North American industry-average EPD exists.
  - Numerous manufacturers in North America have published EPDs.
- **Post-Tensioning Tendons**
  - No post-tensioning tendon data is available within TallyLCA. The concrete reinforcing steel data noted above is used as a proxy.
  - No North American industry-average EPD exists.
  - This data selection favors the concrete system LCAs because concrete reinforcing steel data underestimates the post-tensioning tendon GWP impacts by 32% when compared to the *Suncoast Post-Tensioning System Manufacturer-Specific EPD* (2021).
- **Hot-Rolled Steel Structural Sections**
  - *Fabricated Hot-Rolled Structural Sections Industry-Average EPD* (2016), American Institute of Steel Construction (AISC)
  - Expired 3/31/2021
  - The current AISC *Fabricated Hot-Rolled Sections Industry-Average EPD* (2021) has a 5% GWP (A1-A3) impact increase compared to the expired 2016 EPD.
- **Hot Rolled Steel Hollow Structural Sections**
  - *Steel Tube Hollow Structural Sections Manufacturer-Specific EPD* (2016), Bull Moose Tube Company
  - Expired 9/29/2021
  - No industry-average EPDs are available within TallyLCA.

- **Cold-Formed Structural Steel**
  - Generic LCI data set by TallyLCA; nearly identical to the GWP (A1-A3) impact of the current Steel Framing Industry Association's (SFIA's) *Cold-Formed Steel Framing Industry-Average EPD* (2021)
  - SFIA 2021 EPD expires 5/27/2026
- **Steel Deck**
  - *Steel Deck Industry-Average EPD* (2015), Steel Deck Institute (SDI)
  - Expired 12/15/2020
  - The SDI *Steel Deck Industry-Average EPD* (2022) has a 2% GWP (A1-A3) impact reduction compared to the expired 2015 EPD.
- **Glued-Laminated Timber (Glulam)**
  - *Glued-Laminated Timber Industry-Average EPD* (2013), American Wood Council (AWC) and Canadian Wood Council (CWC)
  - Expired 4/16/2019
  - The current AWC/CWC *Glued-Laminated Timber Industry-Average EPD* (2020) has a 31% GWP (A1-A3) impact reduction compared to the expired 2013 EPD. Biogenic carbon content remains within 1.5% of the value reported in the 2013 EPD as this GWP impact is relative to the dry weight of the wood product.
- **Cross-Laminated Timber (CLT)**
  - Generic LCI data set by TallyLCA; uses the glulam data noted above as a proxy with considerations for variation in CLT density compared to glulam
  - Glulam EPD expired 4/16/2019
  - No North American industry-average CLT EPD exists.
  - See below for a comparison of TallyLCA's CLT data to North American manufacturer CLT EPDs.
- **Gypsum Wall Board, Standard Finish**
  - Generic LCI data set by TallyLCA
  - Expiration unknown
  - No North American industry-average EPD exists.
  - Numerous manufacturers in North America have published EPDs.
- **Gypsum Wall Board, Type X Fire Resistance**
  - Generic LCI data set by TallyLCA
  - Expiration unknown
  - This data selection favors the architectural LCAs because the data underestimates the GWP impact by 48% when compared to the Gypsum Association's industry-average EPD for exterior grade Type X panel (2021) and by 5% when compared to the Gypsum Association's industry-average EPD for interior grade Type X panel (2020).
- **Acoustic Underlayment Mat**
  - No acoustic underlayment mat data set is available within TallyLCA and this material is excluded from the LCA.
  - No North American industry-average EPD exists.
  - Because acoustical underlayment mats are unique to mass timber floor assemblies, estimated GWP impacts of the system's acoustic mat are explored within individual building studies as supplementary results.

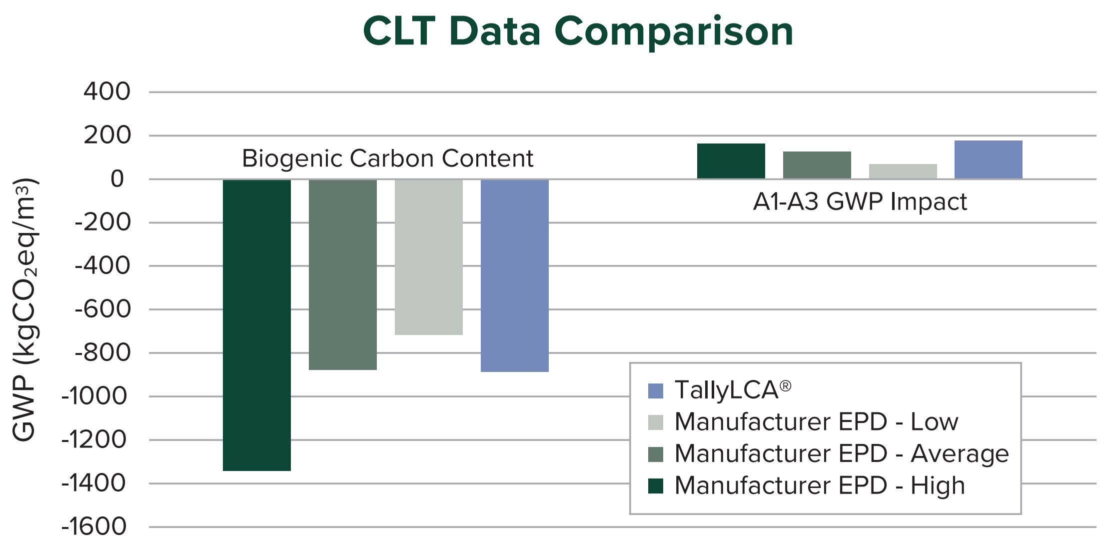

FIGURE 6: CLT data comparison of biogenic carbon content and A1-A3 GWP impact

The change in GWP impacts associated with more current industry-average and manufacturer EPDs are explored within the individual building studies as supplementary results. How these changes affect the reported GWP for each building will depend on relative material volumes and therefore cannot be defined here.

In support of this building study series, all current North American CLT manufacturer-specific EPDs were collected to determine the average and spread of the reported GWP impacts for structural CLT panel products to understand the potential differences, compared to TallyLCA's current data. A1-A3 GWP impacts and biogenic carbon content were collected from the most current EPDs published by seven North American CLT manufacturers, including: Element5 LP, Kalesnikoff, Nordic Structures, SmartLam North America (for both their Dotham, AL and Columbia Falls, MT facilities), Sterling Site Access Solutions,[4] Structurlam Mass Timber Corporation,[5] and Vaagen Timbers. The EPDs used in this average are Type III third-party verified and align with ISO 14025 (ISO 2006) and ISO 21930 requirements. See Environmental Product Declaration Sources for EPD titles and dates of issuance.

Figure 6 compares the CLT data of TallyLCA and the North American manufacturer EPDs. Biogenic carbon is reported separately from the A1-A3 impacts in accordance with ISO 21930 Section 7.2.7. The reported biogenic carbon value is the biogenic carbon content in the CLT when the product leaves the manufacturer, which has the potential to be permanently stored or released at end-of-life. The averages are not weighted based on production volumes and are simple averages. The low and high values reported for biogenic carbon and GWP are the minimum and maximum spread of the manufacturer EPD data and are not necessarily from the same EPD.

The manufacturer A1-A3 GWP impacts are between 2 and 62% less than TallyLCA's A1-A3 data, with an average 30% reduction. This is similar to the 31% reduction for glulam when comparing the 2013 and 2020 glulam EPDs, as previously noted. TallyLCA reports 0.4% less biogenic carbon content than the manufacturer average. Although the average of the mass timber GWP impacts of the most current EPDs are considerably less than the data available in TallyLCA and used for these studies, mass timber material typically has a relatively low embodied carbon impact on the total building, especially when considering biogenic carbon flows, shrinking this effect (Feitel et al., 2021; Jensen et al., 2020; Gu & Bergman, 2018).

Life Cycle Assessment End-of-Life Methodology

End-of-life is an important consideration in understanding holistic embodied carbon impacts and material life cycles, especially for mass timber and its potential to release or store biogenic carbon indefinitely. Table 1 outlines the major material categories within the LCAs and their mix allocation assumptions and methods (see Appendix for TallyLCA's End-of-Life Methodology). Materials without established recycling rates in the U.S. or that are not possible to recycle are assumed to be entirely landfilled, such as gypsum board, glass, insulation, plastics like ethylene propylene diene monomer (EPDM) membranes, and stucco (Tally, 2023).

TallyLCA states that its mass timber end-of-life scenarios are based on Dovetail Partners, Inc.'s 2014 *Municipal Solid Waste and Construction Demolition Wood Waste Generation and Recovery in the United States* report (Howe et al., 2014). This historical data is based on light-frame wood materials. Because mass timber is a relatively new structural product in North America, there is a lack of data regarding end-of-life standard rates and potential. It is reasonable to speculate that mass timber has a higher recovery potential than light-frame wood products because it has a higher value in the sense of structural capabilities, capacity, and aesthetic qualities. Due to its large-format panelization, it also has extremely high recovery and reuse potential at the end of a building's life through deconstruction. TallyLCA does not consider any direct reuse of the mass timber products. Instead, per Table 1, it assumes a combination of incineration, landfill, and recycling/recovery (non-direct reuse), resulting in 31.75% permanent storage of biogenic carbon within the system. The permanent storage of biogenic carbon is achieved assuming 50% of the landfilled material does not decompose or release GHG emissions into the atmosphere based on landfill operating conditions (Stage C). If the best-case scenario of 100% direct reuse is considered, nearly all of the stored biogenic carbon content would be retained permanently in the wood product, resulting in an even lower net GWP impact of the mass timber products and system when considering Module D. See the *Platte Fifteen Life Cycle Assessment* study for an exploration of different mix allocation assumptions (Feitel et al., 2021).

Nez Perce-Clearwater National Forests Supervisor's Office – Kamiah, ID
USDA U.S. Forest Service, Mosaic Architecture, Morrison-Maierle /
Two-story hybrid of mass timber and light-frame wood

Material	Incineration	Landfill	Recycling / Recovery	Accounting Method
Concrete		45%	55%	Recycled into aggregate, credited for avoided burden of production of aggregate, considers impact of grinding energy
CMU, Mortar, Grout		45%	55%	Recycled into coarse aggregate, credited for avoided burden of production of aggregate, considers impact of grinding energy
Steel & Reinforcement		2%	98%	Recycled virgin material is credited for avoided burden of production (net scrap), considers processing impacts
Mass Timber	22%	63.5%	14.5%	Incineration is credited for energy recovery, landfill considers 50% decomposition and release of biogenic carbon (with credit for energy recovery due to landfill gas capture) and 50% is permanently stored, recycling is credited as avoided burden, considers impact of grinding energy
Glass		100%		
Gypsum Board		100%		
Plastic		100%		
Insulation		100%		

TABLE 1: TallyLCA end-of-life mix allocation
Source: Tally, October 2018 and July 2023; Appendix

As noted, Module D is considered outside of a building's system boundary (A-C). TallyLCA does not allow the exclusion or proper separation of Stage C and Module D impacts and benefits from the analysis, so they are included and reported for all materials within the LCAs. Although the effects of stored biogenic carbon have numerically larger GWP impacts and benefits to the system, the concrete and steel materials receive higher relative benefits in Module D as they have higher assumed rates of material recycling and recovery.

Comparative Dollar Cost and Speed of Construction Methodology and Assumptions

The building studies in this series focus primarily on embodied carbon comparisons of structural systems. System, material, and product selections also have implications to dollar cost and construction schedules.

Innovation is often thwarted by dollar cost premiums, whether real or perceived, and this is often the case with mass timber; initial pricing (typically material procurement-focused) shows a cost premium over conventional materials. Unfamiliarity with the product type and installation methods can also hinder cost competitiveness.

Therefore, to illustrate the cost of mass timber holistically, it is important to consider material dollar cost as well as the impact on labor and construction speed. Mass timber systems in repetitive multi-story configurations can have speed of construction benefits. Exposed wood can also serve as a finish material, saving the cost of additional materials and time.

The dollar cost and speed of construction analyses for the studies are performed by either the reference building's general contractor or other construction professionals, who are independent of the alternative designs, LCAs, and study authorship. The analyses rely on the reference mass timber buildings' actual construction costs, construction schedules, and construction dates. Comparative pricing is developed considering the historic material, labor, and unit prices to match the date of the mass timber building procurement and installation costs.

The dollar cost analyses' scope includes material, installation, labor, site logistics, equipment, and waste. The comparative material costs, structure cost, and total cost to the owner are reported on a relative percentage basis. Excluded from the cost analyses are the developer's liability insurance premiums, any financial benefits or losses to the developer associated with the time-value of money, any financial benefits or losses to the developer associated with the lease or sale market value of the building, and any potential carbon credits or carbon taxes. The specific dollar cost and schedule information are discussed within each building study, along with any variations from this general methodology.

Auraria Ballfield Office – Denver, CO
Columbia Ventures, SAR+, KL&A Engineers & Builders /
Four-story mass timber building with no below-grade levels

Conclusion

As popularity and implementation of mass timber buildings has accelerated in the U.S., the desire and need for data on mass timber systems has increased.

This *Mass Timber Comparative Life Cycle Assessment Series* endeavors to explore and answer the questions:

- How does mass timber compare to traditional structural systems?
- Is mass timber sustainable?
- What are the associated dollar cost premiums?

The series focuses on the embodied carbon and economic implications of selecting mass timber structural systems, using WBLCA, dollar cost, and speed of construction comparative analyses. The individual building studies are based on real mass timber building designs for projects located in the United States, and are compared to functionally equivalent designs using traditional structural systems such as steel or concrete.

This document is intended to serve as an introduction to the series and to define the general methodology, approach, scope, and code compliance of the comparative designs, LCAs, and dollar cost analyses common to each building study. The authors have endeavored to be transparent in methodology, scope, and assumptions.

The series has been developed to support the adoption, implementation, and success of mass timber buildings in North America as one of many necessary embodied carbon reduction strategies. Individual building studies will be published periodically. Please follow along on the WoodWorks website at www.woodworks.org/mass-timber-comparative-LCA-series.

End Notes

1 www.woodworks.org/resources/platte-fifteen-life-cycle-assessment/

2 Functionally equivalent means the same design criteria as the reference systems—i.e., equivalent floor area, site orientation, occupancy, general programmatic layout, geographic location, load criteria, and performance requirements, in accordance with ISO 14044 4.2.3.7 and ASTM E2921.

3 In addition to national level reporting as required by ISO 21930 "…documented risk assessments provide the basis upon which raw materials sourced from Canada and the United States can be deemed to meet the 'Legal Sources' category" (ASTM International, 2021).

4 The referenced EPD is Sterling Site Structural Solutions' TerraLam Structural CLT product EPD. Sterling Structural is owned by Sterling Site Access Solutions, LLC (Sterling Site Structural Solutions, 2022).

5 At the time of this writing, Structurlam Mass Timber Corporation's CLT EPD was available and current, and was therefore included in the EPD study. However, Structurlam was purchased by Mercer International in 2023.

Sources

Architecture 2030. (2023, July). *Why the Built Environment?*

ASTM International. (2021). Standard Practice for Categorizing Wood and Wood-Based Products According to Their Fiber Sources. (ASTM D7612-21).

ASTM International. (2022). Standard Practice for Minimum Criteria for Comparing Whole Building Life Cycle Assessments for Use with BuildingCodes, Standards, and Rating Systems. (ASTM E2921-16a).

Carbon Leadership Forum. (2023, July). *The Embodied Carbon Challenge*.

Dovetail Partners, Inc. (2013). *Carbon in Wood Products – The Basics*.

Environment and Climate Change Canada. (2021). *National Inventory Report 1990-2021: Greenhouse Gas Sources*.

Feitel, A., Redwine, B., Kingsley, G. (2021). *Platte Fifteen Life Cycle Assessment*. Think Wood, WoodWorks – Wood Products Council.

Fernholz, K., Jacobs, M., & Erickson, G. (2022, Revised 2023). *Mass Timber and Tall Wood Buildings: An Update*. Dovetail Partners.

Gu, H., Bergman, R. (2018). *Life Cycle Assessment and Environmental Building Declaration for the Design Building at the University of Massachusetts*. USDA United States Forest Service Forest Products Laboratory.

Howe, D. J., Bowyer, D. J., Pepke, D. E., Frank, M., Fernholz, K. (2014). *Municipal Solid Waste (MSW) and Construction and Demolition (C&D) Wood Waste Generation and Recovery in the United States*. Dovetail Partners Inc.

International Organization for Standardization. (2006). Environmental labels and declarations – Type III environmental declarations – Principles and procedures. (ISO 14025:2006).

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

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

Jensen, A., Sehovic, Z., St. Clair Knobloch, N., Klein, J., Richardson, P., Janiski, J. (2020, July 9). *Mass Timber Solutions for Eight Story Mixed-Use Buildings: A Comparative Study of GHG Emissions*. Preprints 2020, 2020070175.

King, B. (2017). *The New Carbon Architecture: Building to Cool the Climate*. New Society Publishes.

Oswalt, S. N., Miles, P. D., Pugh, S. A., Smith, W. B. (2018). *Forest Resources of the United States, 2017: A Technical Document Supporting the Forest Service 2020 RPA Assessment*. U.S. Department of Agriculture, United States Forest Service.

Simonen, K. (2014). *Pocket Architecture: Technical Design Series – Life Cycle Assessment* (pp. 37-41).

Tally. (2023, July). *Methods*.

Tally, C. (Director). (October 2018). *Tally 2019 Webinar Series: Biogenic Carbon 101* [Motion Picture].

United States Environmental Protection Agency. (2021). *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2019*.

WoodWorks – Wood Products Council. (2023, July). *Biogenic Carbon Accounting in WBLCA Tools*.

Environmental Product Declaration Sources

American Institute of Steel Construction. (2016). *Environmental Product Declaration Fabricated Hot-Rolled Structural Sections*. UL Environment.

American Institute of Steel Construction. (2021). *Environmental Product Declaration Fabricated Hot-Rolled Structural Sections*. UL Environment.

American Wood Council, Canadian Wood Council. (2013). *Environmental Product Declaration North American Glued Laminated Timbers*. UL Environment.

American Wood Council, Canadian Wood Council. (2020). *Environmental Product Declaration North American Glued Laminated TImber*. UL Environment.

Bull Moose Tube Company. (2016). *Environmental Product Declaration Steel Tubes – Hollow Structural Sections, Mechanical Tube, and Sprinkler Pipe*. UL Environment.

Canadian Concrete Masonry Producers Association. (2022). *Environmental Product Declaration: Normal Weight and Lightweight Concrete Block Masonry Units as Manufactured by Members of the Canadian Concrete Masonry Producers Association*. ASTM International.

Canadian Precast/Prestressed Concrete Institute and Precast/Prestressed Concrete Institute. (2019). *Structural Precast Concrete Industry Wide EPD*. ASTM International.

Commercial Metals Company. (2015). *Environmental Product Declaration Fabricated Concrete Reinforcing Steel*. ASTM International.

Concrete Reinforcing Steel Institute. (2022). *Environmental Product Declaration Steel Reinforcement Bar*. ASTM International.

Element5 LP – Modern Timber Buildings. (2022). *An Environmental Product Declaration According to ISO 14025:2006 and ISO 21930:2017 – A Company-Specific Cradle-to-Gate EPD for Element5 Cross-Laminated Timber (CLT)*. ASTM International.

Gypsum Association. (2020). *An Environmental Product Declaration: 5/8" Type X Conventional Gypsum Board*. NSF Certification, LLC.

Gypsum Association. (2021). *An Environmental Product Declaration: 1/2" and 5/8" Glass-mat Gypsum Boards*. ASTM International.

Kalesnikoff. (2022). *Environmental Product Declaration Cradle to Gate EPD for Cross Laminated Timber produced by Kalesnikoff in South Slocan, BC*. ASTM International.

National Ready Mixed Concrete Association. (2019, Updated 2020). *Environmental Product Declaration NRMCA Member Industry-Average EPD for Ready Mixed Concrete*. NSF Certification, LLC.

National Ready Mixed Concrete Association. (2022). *Environmental Product Declaration NRMCA Member Industry-Average EPD for Ready Mixed Concrete*. NSF Certification, LLC.

Nordic Structures. (2023). *Environmental Product Declaration (EPD) Nordic X-Lam*. CSA Group.

SmartLam North America. (2021). *Environmental Product Declaration Cross-Laminated Timber (CLT) Dothan, Alabama*. SCS Global Services.

SmartLam North America. (2021). *Environmental Product Declaration Cross-Laminated Timber (CLT) Columbia Falls, Montana*. SCS Global Services.

Steel Deck Institute. (2022). *Environmental Product Declaration Steel Deck – Steel Roof Deck, Steel Floor Deck*. UL Environment.

Steel Deck Institute. (2015). *Environmental Product Declaration Steel Deck – Steel Roof Deck, Steel Floor Deck*. UL Environment.

Steel Framing Industry Association. (2021). *Environmental Product Declaration SFIA | Cold-Formed Steel Framing*. SCS Global Services.

Sterling Site Access Solutions, LLC. (2022). *Environmental Product Declaration in Accordance with EN15804+A2 & ISO 14025 / ISO 21930, TerraLam® Structural CLT*. EPD Hub.

Structurlam Mass Timber Corporation. (2020). *Environmental Product Declaration Crosslam CLT – EPD for Cross Laminated Timber produced by Structurlam in Okanagan Falls, BC*. ASTM International.

Suncoast Post-Tension, Ltd. (2021). *Environmental Product Declaration Suncoast | Post-Tension Post-Tensioning System*. SCS Global Services.

Vaagen Timbers. (2021). *Environmental Product Declaration (EPD) for Cross Laminated Timber produced by Vaagen Timbers in Colville, WA*. ASTM International.

Appendix

Calculation Methodology

LIFE CYCLE ASSESSMENT METHODS

The following provides a description of terms and methods associated with the use of Tally to conduct life cycle assessment for construction works and construction products. Tally methodology is consistent with LCA standards ISO 14040-14044, ISO 21930:2017, ISO 21931:2010, EN 15804:2012, and EN 15978:2011. For more information about LCA, please refer to these standards or visit www.choosetally.com.

Studied objects

The life cycle assessment (LCA) results reported represent an analysis of a single building, multiple buildings, or a comparative analysis of two or more building design options. The assessment may represent the complete architectural, structural, and finish systems of the building(s) or a subset of those systems. This may be used to compare the relative environmental impacts associated with building components or for comparative study with one or more reference buildings. Design options may represent a full or partial building across various stages of the design process, or they may represent multiple schemes of a full or partial building that are being compared to one another across a range of evaluation criteria.

Functional unit and reference unit

A functional unit is the quantified performance of a product, building, or system that defines the object of the study. The functional unit of a single building should include the building type (e.g. office, factory), relevant technical and functional requirements (e.g. regulatory requirements, energy performance), pattern of use (e.g. occupancy, usable floor area), and the required service life. For a design option comparison of a partial building, the functional unit is the complete set of building systems or products that perform a given function. It is the responsibility of the modeler to assure that reference buildings or design options are functionally equivalent in terms of scope and relevant performance. The expected life of the building has a default value of 60 years and can be modified by the modeler.

The reference unit is the full collection of processes and materials required to produce a building or portion thereof and is quantified according to the given goal and scope of the assessment over the full life of the building. If construction impacts are included in the assessment, the reference unit also includes the energy, water, and fuel consumed on the building site during construction. If operational energy is included in the assessment, the reference unit includes the electrical and thermal energy consumed on site over the life of the building.

Data source

Tally utilizes a custom designed LCA database that combines material attributes, assembly details, and architectural specifications with environmental impact data resulting from the collaboration between KieranTimberlake and thinkstep. LCA modeling was conducted in GaBi 8.5 using GaBi 2018 databases and in accordance with GaBi databases and modeling principles.

The data used are intended to represent the US and the year 2017. Where representative data were unavailable, proxy data were used. The datasets used, their geographic region, and year of reference are listed for each entry. An effort was made to choose proxy datasets that are technologically consistent with the relevant entry.

Data quality and uncertainty

Uncertainty in results can stem from both the data used and their application. Data quality is judged by: its measured, calculated, or estimated precision; its completeness, such as unreported emissions; its consistency, or degree of uniformity of the methodology applied on a study serving as a data source; and geographical, temporal, and technological representativeness. The GaBi LCI databases have been used in LCA models worldwide in both industrial and scientific applications. These LCI databases have additionally been used both as internal and critically reviewed and published studies. Uncertainty introduced by the use of proxy data is reduced by using technologically, geographically, and/or temporally similar data. It is the responsibility of the modeler to appropriately apply the predefined material entries to the building under study.

System boundaries and delimitations

The analysis accounts for the full cradle to grave life cycle of the design options studied across all life cycle stages, including material manufacturing, maintenance and replacement, and eventual end of life. Optionally, the construction impacts and operational energy of the building can be included within the scope. Product stage impacts are excluded for materials and components indicated as existing or salvaged by the modeler. The modeler defines whether the boundary includes or excludes the flow of biogenic carbon, which is the carbon absorbed and generated by biological sources (e.g. trees, algae) rather than from fossil resources.

Architectural materials and assemblies include all materials required for the product's manufacturing and use including hardware, sealants, adhesives, coatings, and finishing. The materials are included up to a 1% cut-off factor by mass except for known materials that have high environmental impacts at low levels. In these cases, a 1% cut-off was implemented by impact.

Calculation Methodology

LIFE CYCLE STAGES

The following describes the scope and system boudaries used to define each stage of the life cycle of a building or building product, from raw material acquisition to final disposal. For products listed in Tally as Environmental Product Declarations (EPD), the full life cycle impacts are included, even if the published EPD only includes the Product stage [A1-A3].

Product [EN 15978 A1 - A3]

This encompasses the full manufacturing stage, including raw material extraction and processing, intermediate transportation, and final manufacturing and assembly. The product stage scope is listed for each entry, detailing any specific inclusions or exclusions that fall outside of the cradle to gate scope. Infrastructure (buildings and machinery) required for the manufacturing and assembly of building materials are not included and are considered outside the scope of assessment.

Transportation [EN 15978 A4]

This counts transportation from the manufacturer to the building site during the construction stage and can be modified by the modeler.

Construction Installation [EN 15978 A5] (Optional)

This includes the anticipated or measured energy and water consumed on-site during the construction installation process, as specified by the modeler.

Maintenance and Replacement [EN 15978 B2-B5]

This encompasses the replacement of materials in accordance with their expected service life. This includes the end of life treatment of the existing products as well as the cradle to gate manufacturing and transportation to site of the replacement products. The service life is specified separately for each product. Refurbishment of materials marked as existing or salvaged by the modeler is also included.

Operational Energy [EN 15978 B6] (Optional)

This is based on the anticipated or measured energy and natural gas consumed at the building site over the lifetime of the building, as indicated by the modeler.

End of Life [EN 15978 C2-C4]

This includes the relevant material collection rates for recycling, processing requirements for recycled materials, incineration rates, and landfilling rates. The impacts associated with landfilling are based on average material properties, such as plastic waste, biodegradable waste, or inert material. Stage C2 encompasses the transport from the construction site to end-of-life treatment based on national averages. Stages C3-C4 account for waste processing and disposal, i.e., impacts associated with landfilling or incineration.

Module D [EN 15978 D]

This accounts for reuse potentials that fall beyond the system boundary, such as energy recovery and recycling of materials. Along with processing requirements, the recycling of materials is modeled using an avoided burden approach, where the burden of primary material production is allocated to the subsequent life cycle based on the quantity of recovered secondary material. Incineration of materials includes credit for average US energy recovery rates.

PRODUCT	CONSTRUCTION	USE	END-OF-LIFE	MODULE D
A1. Extraction **A2. Transport (to factory)** **A3. Manufacturing**	**A4. Transport (to site)** ***A5. Construction Installation***	B1. Use **B2. Maintenance** **B3. Repair** **B4. Replacement** **B5. Refurbishment** ***B6. Operational energy*** B7. Operational water	C1. Demolition **C2. Transport (to disposal)** **C3. Waste processing** **C4. Disposal**	**D. Benefits and loads beyond the system boundary from:** **1. Reuse** **2. Recycling** **3. Energy recovery**

Life-Cycle Stages as defined by EN 15978. Processes included in Tally modeling scope are shown in bold. Italics indicate optional processes.

Calculation Methodology

ENVIRONMENTAL IMPACT CATEGORIES

A characterization scheme translates all emissions and fuel use associated with the reference flow into quantities of categorized environmental impact. As the degree that the emissions will result in environmental harm depends on regional ecosystem conditions and the location in which they occur, the results are reported as impact potential. Potential impacts are reported in kilograms of equivalent relative contribution (eq) of an emission commonly associated with that form of environmental impact (e.g. kg CO_2eq).

The following list provides a description of environmental impact categories reported according to the TRACI 2.1 characterization scheme, the environmental impact model developed by the US EPA to quantify environmental impact risk associated with emissions to the environment in the United States. TRACI is the standard environmental impact reporting format for LCA in North America. Impacts associated with land use change and fresh water depletion are not included in TRACI 2.1. For more information on TRACI 2.1, reference Bare 2010, EPA 2012, and Guinée 2001. For further description of measurement of environmental impacts in LCA, see Simonen 2014.

Acidification Potential (AP) kg SO_2eq

A measure of emissions that cause acidifying effects to the environment. The acidification potential is a measure of a molecule's capacity to increase the hydrogen ion (H^+) concentration in the presence of water, thus decreasing the pH value. Potential effects include fish mortality, forest decline, and the deterioration of building materials.

Eutrophication Potential (EP) kg Neq

A measure of the impacts of excessively high levels of macronutrients, the most important of which are nitrogen (N) and phosphorus (P). Nutrient enrichment may cause an undesirable shift in species composition and elevated biomass production in both aquatic and terrestrial ecosystems. In aquatic ecosystems, increased biomass production may lead to depressed oxygen levels caused by the additional consumption of oxygen in biomass decomposition.

Global Warming Potential (GWP) kg CO_2eq

A measure of greenhouse gas emissions, such as carbon dioxide and methane. These emissions are causing an increase in the absorption of radiation emitted by the earth, increasing the natural greenhouse effect. This may, in turn, have adverse impacts on ecosystem health, human health, and material welfare.

Ozone Depletion Potential (ODP) kg CFC-11eq

A measure of air emissions that contribute to the depletion of the stratospheric ozone layer. Depletion of the ozone leads to higher levels of UVB ultraviolet rays reaching the earth's surface with detrimental effects on humans and plants. As these impacts tend to be very small, ODP impacts can be difficult to calculate and are prone to a larger margin of error than the other impact categories.

Smog Formation Potential (SFP) kg O_3eq

A measure of ground level ozone, caused by various chemical reactions between nitrogen oxides (NO_x) and volatile organic compounds (VOCs) in sunlight. Human health effects can result in a variety of respiratory issues, including increasing symptoms of bronchitis, asthma, and emphysema. Permanent lung damage may result from prolonged exposure to ozone. Ecological impacts include damage to various ecosystems and crop damage.

Primary Energy Demand (PED) MJ (lower heating value)

A measure of the total amount of primary energy extracted from the earth. PED tracks energy resource use, not the environmental impacts associated with the resource use. PED is expressed in energy demand from non-renewable resources and from renewable resources. Efficiencies in energy conversion (e.g. power, heat, steam, etc.) are taken into account when calculating this result.

Non-Renewable Energy Demand MJ (lower heating value)

A measure of the energy extracted from non-renewable resources (e.g. petroleum, natural gas, etc.) contributing to the PED. Non-renewable resources are those that cannot be regenerated within a human time scale. Efficiencies in energy conversion (e.g. power, heat, steam, etc.) are taken into account when calculating this result.

Renewable Energy Demand MJ (lower heating value)

A measure of the energy extracted from renewable resources (e.g. hydropower, wind energy, solar power, etc.) contributing to the PED. Efficiencies in energy conversion (e.g. power, heat, steam, etc.) are taken into account when calculating this result.

LCI Data

END-OF-LIFE [C2-C4]

A Life Cycle Inventory(LCI) is a compilation and quantification of inputs and outputs for the reference unit.The following LCI provides a summary of all energy, construction, transportation, and material inputs present in the study. Materials are listed in alphabetical order along with a list of all Revit families and Tally entries in which they occur, along with any notes and system boundaries accompanying their database entries. Each entry lists the detailed scope for the LCI data sources used from the GaBi LCI database and identifies the LCI data source.

For LCI data sourced from an Environmental Product Declaration (EPD), the product manufacturer, EPD identification number, and Program Operator are listed. Where the LCI source does not provide data for all life cycle stages, default North American average values are used. This is of particular importance for European EPD sources, as EPD data are generally only provided for the product stage, and North American average values are used for the remaining life cycle stages.

Where specific quantities are associated with a data entry, such as user inputs, energy values, or material mass, the quantity is listed on the same line as the title of the entry.

TRANSPORTATION [A4]

Default transportation values are based on the three-digit material commodity code in the 2012 Commodity Flow Survey by the US Department of Transportation Bureau of Transportation Statistics and the US Department of Commerce where more specific industry-level transportation is not available.

Transportation by Barge
Scope:
The data set represents the transportation of 1 kg of material from the manufacturer location to the building site by barge.

LCI Source:
GLO: Average ship, 1500t payload capacity/ canal ts (2017)
US: Diesel mix at filling station ts (2014)

Transportation by Container Ship
Scope:
The data set represents the transportation of 1 kg of material from the manufacturer location to the building site by container ship.

LCI Source:
GLO: Container ship, 27500 dwt payload capacity, ocean going ts (2017)
US: Heavy fuel oil at refinery (0.3wt.% S) ts (2014)

Transportation by Rail
Scope:
The data set represents the transportation of 1 kg of material from the manufacturer location to the building site by cargo rail.

LCI Source:
GLO: Rail transport cargo - Diesel, average train, gross tonne weight 1000t / 726t payload capacity ts (2017)
US: Diesel mix at filling station ts (2014)

Transportation by Truck
Scope:
The data set represents the transportation of 1 kg of material from the manufacturer location to the building site by diesel truck.

LCI Source:
US: Truck - Trailer, basic enclosed / 45,000 lb payload - 8b ts (2017)
US: Diesel mix at filling station ts (2014)

LCI Data (continued)

END-OF-LIFE [C2-C4]

Specific end-of-life scenarios are detailed for each entry based on the US construction and demolition waste treatment methods and rates in the 2016 WARM Model by the US Environmental Protection Agency except where otherwise specified. Heterogeneous assemblies are modeled using the appropriate methodologies for the component materials.

End-of-Life Landfill

Scope:

Materials for which no recycling or incineration rates are known, no recycling occurs within the US at a commercial scale, or which are unable to be recycled are landfilled. This includes glass, drywall, insulation, and plastics. The solids contents of coatings, sealants, and paints are assumed to go to landfill, while the solvents or water evaporate during installation. Where the landfill contains biodegradable material, the energy recovered from landfill gas utilization is reflected as a credit in Module D.

LCI Source:

US: Glass/inert on landfill ts (2017)
US: Biodegradable waste on landfill, post-consumer ts (2017)
US: Plastic waste on landfill, post-consumer ts (2017)

Concrete End-of-Life

Scope:

Concrete (or other masonry products) are recycled into aggregate or general fill material or they are landfilled. It is assumed that 55% of the concrete is recycled. Module D accounts for both the credit associated with off-setting the production aggregate and the burden of the grinding energy required for processing.

LCI Source:

US: Diesel mix at refinery ts (2014)
GLO: Fork lifter (diesel consumption) ts (2016)
EU - 28 Gravel 2/32 ts (2017)
US: Glass/inert on landfill ts (2017)

Metals End-of-Life

Scope:

Metal products are modeled using the avoided burden approach. The recycling rate at end of life is used to determine how much secondary metal can be recovered after having subtracted any scrap input into manufacturing (net scrap). Net scrap results in an environmental credit in Module D for the corresponding share of the primary burden that can be allocated to the subsequent product system using secondary material as an input. If the value in Module D reflects an environmental burden, then the original product (A1-A3) contains more secondary material than is recovered.

LCI Source:

Aluminum - RNA: Primary Aluminum Ingot AA/ts (2010)
Aluminum - RNA: Secondary Aluminum Ingot AA/ts (2010)
Brass - GLO: Zinc mix ts (2012)
Brass - GLO: Copper (99.99% cathode) ICA (2013)
Brass - EU-28: Brass (CuZn20) ts (2017)
Copper - DE: Recycling potential copper sheet ts (2016)
Steel - GLO: Value of scrap worldsteel (2014)
Zinc - GLO: Special high grade zinc IZA (2012)

Wood End-of-Life

Scope:

End of Life waste treatment methods and rates for wood are based on the 2014 Municipal Solid Waste and Construction Demolition Wood Waste Generation and Recovery in the United States report by Dovetail Partners, Inc. It is assumed that 63.5% of wood is sent to landfill, 22% to incineration, and 14.5% to recovery.

LCI Source:

US: Untreated wood in waste incineration plant ts (2017)
US: Wood product (OSB, particle board) waste in waste incineration plant ts (2017)
US: Wood products (OSB, particle board) on landfill, post-consumer ts (2017)
US: Untreated wood on landfill, post-consumer ts (2017)
RNA: Softwood lumber CORRIM (2011)

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