Life Cycle Assessment

of

Katerra's Cross-Laminated Timber (CLT)

and Catalyst Building

Final Report

November 2019

Prepared for

Katerra

by the

Carbon Leadership Forum

and the

Center for International Trade in Forest Products

at the

UNIVERSITY *of* WASHINGTON

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Citations

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Introduction

Katerra has developed its own cross-laminated timber (CLT) manufacturing facility in Spokane Valley, Washington. This 25,100 m^2 (270,000 ft^2) factory is the largest CLT manufacturing facility in the world, and is capable of producing approximately 187,000 m^3 of CLT per year. Katerra has also established a vertically integrated supply chain to provide the wood for the CLT factory. Production started in summer of 2019.

Katerra commissioned the Carbon Leadership Forum (CLF) and Center for International Trade in Forest Products (CINTRAFOR) at the University of Washington to analyze the environmental impacts of its CLT as well as the Catalyst Building in Spokane, Washington. The Catalyst is a 15,690 m^2 (168,800 ft^2), five-story office building that makes extensive use of CLT as a structural and design element. Jointly developed by Avista and McKinstry, Katerra largely designed and constructed the building, and used CLT produced by Katerra's new factory. Performing a life cycle assessment (LCA) on Katerra's CLT will allow Katerra to explore opportunities for environmental impact reduction along their supply chain and improve their CLT production efficiency. Performing an LCA on the Catalyst Building will enable Katerra to better understand life cycle environmental impacts of mass timber buildings and identify opportunities to optimize environmental performance of mid-rise CLT structures.

The goal, scope, methodology, and results of this analysis are detailed in this report.

Goal and scope

The goal and scope of the LCA are described in this section.

Goal

The goal of this life cycle assessment (LCA) is to understand the environmental impacts of Katerra's newly-established CLT supply chain and manufacturing facility, and highlight "hot-spots" or opportunities for impact reduction. To do so, the research team performed the following activities:

- The CINTRAFOR research team performed an LCA of Katerra's CLT manufacturing facility, which was located in Spokane Valley, Washington, taking into account the geographic origin of the lumber, which was from British Columbia, Canada. The research time analyzed the LCA results to identify "hot-spots" of environmental impact along the supply chain.

- The CLF research team performed a whole building LCA (WBLCA) of a new mass timber building that was largely designed and constructed by Katerra. This building, named the Catalyst Building, is located in Spokane, Washington was under construction at the time of authoring this report. The research team analyzed the LCA results to identify "hot-spots" of environmental impact in the building.
    - At the request of Katerra, this case study assumed that all of the CLT in the building was produced at Katerra's CLT supply chain/factory, but in reality, only the 5-ply floor panels on this project were produced by Katerra. Structurlam provided the 3-ply CLT for the cladding and the 7-ply CLT for the CLT shear walls because the Katerra production facility had not ramped up yet to produce 3-ply and 7-ply CLT in time for the Catalyst project schedule.
    - As a part of the WBLCA, the CLF research team also performed a comparison of the preliminary vs final design of the enclosure and the accompanying energy use intensity (EUI).

Five environmental impact measures were assessed and characterized using the Tool for the Reduction and Assessment of Chemical and other Environmental Impacts (TRACI) 2.1. Primary energy consumption was also assessed. These impact measures and their accompanying units of measurement are:

1. Global warming potential (GWP) in kilograms of carbon dioxide equivalent (kg CO2e)
2. Acidification potential (AP) in kilograms of sulfur dioxide equivalent (kg SO2e)
3. Eutrophication potential (EP) in kilograms of nitrogen equivalent (kg Ne)
4. Ozone depletion potential (ODP) in kilograms of trichlorofluoromethane (CFC11) equivalent (kg CFC11e)
5. Smog formation potential (SFP) in kilograms of ozone equivalent (kg O3e)
6. Primary energy consumption (MJ)

The later in-depth analysis of the results focused on global warming potential (GWP), since this is the key impact measure of concern in the building industry.

The results of this study are intended for use by the internal Katerra team. The results are also tentatively intended to be released to the public at the discretion of Katerra.

A third-party review will not be performed since the results of this study are not intended for use in comparative assertions. This means that these results cannot be definitely compared with other whole building LCAs to determine if one or the other is "better" or "worse"

The goal of the whole building LCA can be captured by a framework that is being developed as a part of ongoing efforts to standardize building LCA reporting, also referred to as an "LCA taxonomy." The goal portion LCA taxonomy is presented in Table 1.

Table 1. LCA taxonomy goal description.

LCA taxonomy	**Project information**
Assessment goal	
• Intended application	To understand the environmental impacts of Katerra's CLT manufacturing supply chain, and the environmental impact of the Catalyst building.
• Reasons for carrying out the study	To help Katerra reduce its environmental impacts.
• Intended audience	Internal Katerra team.
• Whether results are intended to be used in comparative assertions	No comparative assertions will be made
Background information on assessment	
General information on LCA	
• Date of LCA assessment	November 2019
• Assessment stage: Project phase at time of LCA assessment	Construction phase
• Client for assessment	Katerra
• Name and qualification of LCA assessor	• Kate Simonen, AIA, LEED, PE, SE (PI) • Indroneil Ganguly, Ph.D. (Co-PI) • Francesca Pierobon, Ph.D. • Monica Huang, EIT, MSCE • Cindy X. Chen, Ph.D.
• Organization of assessor	The Carbon Leadership Forum (CLF) and Center for International Trade of Forest Products (CINTRAFOR) at the University of Washington (UW)
Verification	Verification not performed
LCA data and methods	
• Source, type, and quality of LCA data (reference date)	• For CLT LCA: SimaPro v9 (2019). See Table 4 for additional information. • For case study building: Athena 5.2 (2016) and a few EPDs
• LCA impacts and assessment method including version number and reference	• Characterization method: TRACI 2.1 • LCA impacts assessed: ○ Global warming potential (GWP) in kilograms of carbon dioxide equivalent (kg CO2e)

LCA taxonomy	Project information
	○ Acidification potential (AP) in kilograms of sulfur dioxide equivalent (kg SO2e) ○ Eutrophication potential (EP) in kilograms of nitrogen equivalent (kg Ne) ○ Ozone depletion potential (ODP) in kilograms of trichlorofluoromethane (CFC11) equivalent (kg CFC11e) ○ Smog formation potential (SFP) in kilograms of ozone equivalent (kg O3e) ○ Primary energy consumption (MJ)
Assumptions and scenarios	
• HVAC, natural ventilation and daylight simulation performed	HVAC and daylighting – yes. Natural ventilation – no.
• Source, type, and quality of building data	The material quantities were provided by Katerra. This information is considered to be highly accurate.
• BIM model available (Y/N)	Yes, but not currently used in this study

Scope

The scopes of the CLT LCA and the building LCA are described separately in this section. Each subsection herein describes the life cycle stages and physical system boundaries in each analysis.

CLT

CLT panels manufactured at the Katerra facility are produced with 3-ply, 5-ply, 7-ply, and 9-ply layups, providing a catalog of panel types that can be specified for a specific design application. The first layup type being manufactured are 5-ply master panels 6.60 inches in total thickness and approximately 60 feet in length and 10 feet in width. The wood species combination used for the CLT panels being investigated in this project is spruce-pine-fir (SPF), which has a bone-dry density of 420 kg/m^3. Future plans for production can include panels ranging from 3.24 inches in total thickness for 3-ply, up to 12.42 inches in thickness for 9-ply. The LCA model is based on a functional unit of 1 m^3 of CLT panel.

The life cycle scope of this analysis includes:

- A1: Forestry operation and lumber production
- A2: Transportation from sawmills to CLT manufacturing facility
- A3: Onsite CLT manufacturing

Figure 1 outlines the processes involved in the CLT production system, i.e. the system boundary of the analysis. The system being evaluated begins at the resources extraction phase and ends at the exit point of the manufacturing facility. The final impacts modeled are based on the input and output data for energy and materials. Emissions from fossil fuel are accounted for in the final results, while biogenic carbon from biomass-based fuels is not included in the results. A detailed description associated with biogenic carbon and carbon storage is included in the section “Results” > “Catalyst Building” > “Carbon storage.”

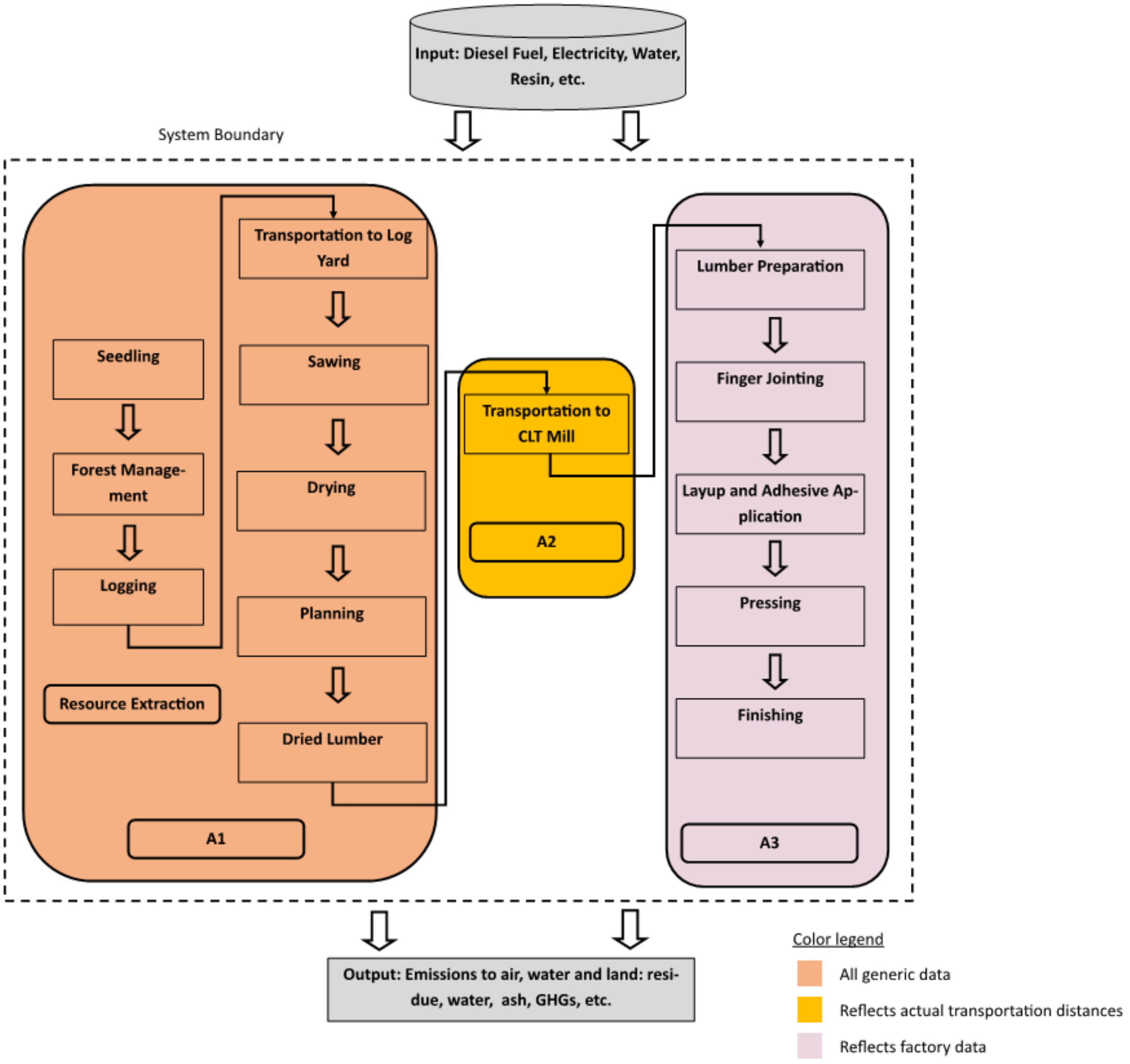


Figure 1. System boundary for CLT production.

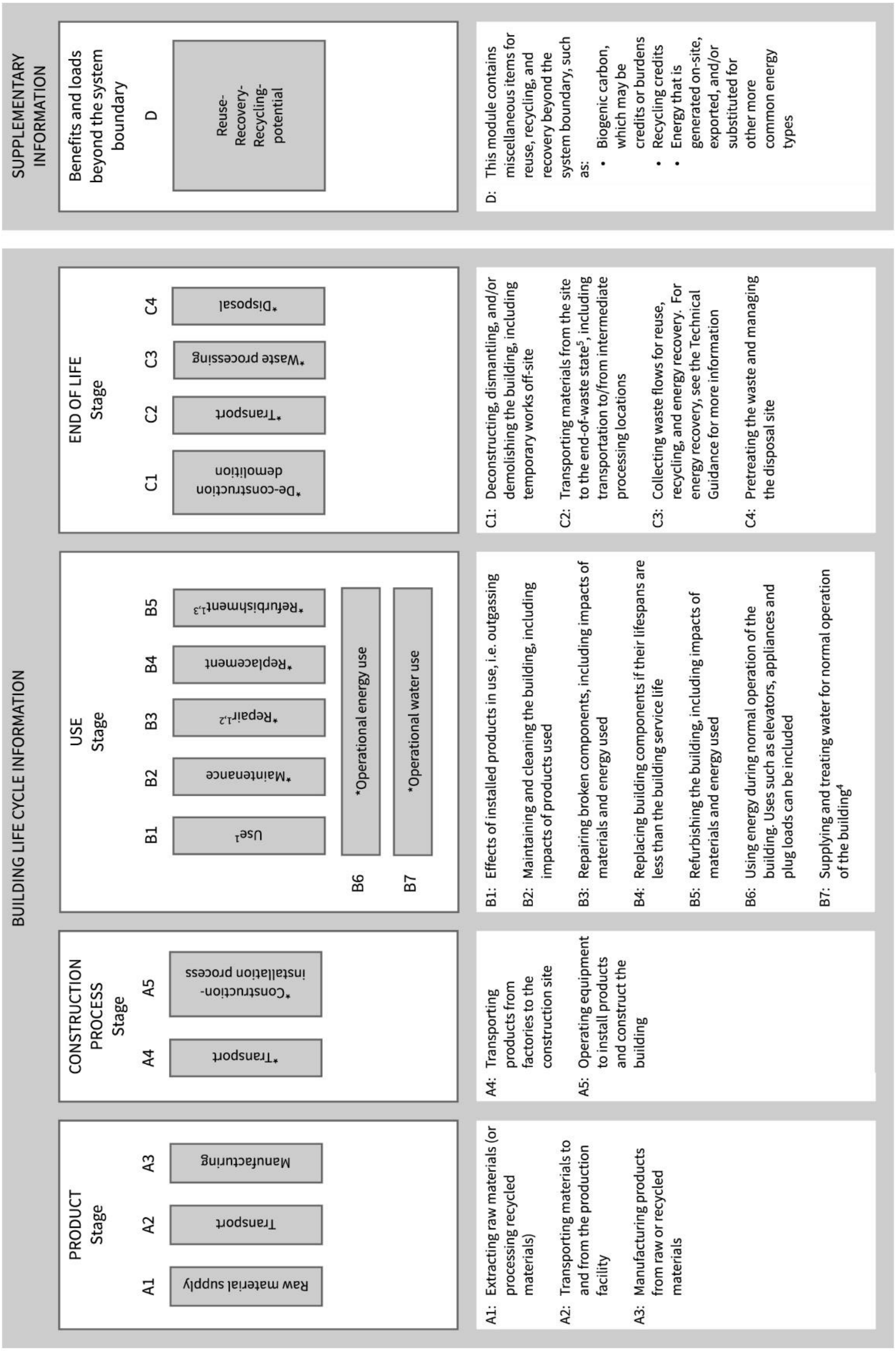
Building scope

The life cycle scope of the building LCA includes:

- Stage A: Product and construction process stages
    - A1: Raw material extraction
    - A2: Transportation of materials from material supply to the manufacturing facility
    - A3: Product and material processing/manufacturing
    - A4: Transportation of materials from manufacturing facility to the building site
    - A5: Construction and installation
- Stage B: Use stage
    - B6: Operational energy use only
- Stage D: Benefits and loads beyond the system boundary
    - Biogenic carbon storage only

For reference, Figure 2 presents the standard life cycle stages of a building based on EN 15978 and ISO 21930.

This study did not evaluate the impacts of materials in life cycle stage B (such as use and maintenance during building life) and stage C (such as demolition and disposal at end-of-life) because the data for these stages tend to be highly uncertain and hypothetical, and not enough information about these life cycle stages for this building were available at the time of the analysis.



* Scenario descriptions required
[1] These modules are currently not well-supported by LCA databases and tools.
[2] Repair is defined as "returning an item to an acceptable condition by the renewal, replacement or mending of worn, damaged or degraded parts" [9].
[3] Refurbishment is defined as "modification and improvements to an existing building in order to bring it up to an acceptable condition" [9].
[4] Note that tracking operational water use is not common in whole building LCA tools and requires further development of the methodology.
[5] EN 15978 defines the end-of-waste state in Section 7.4.5.4.

Figure 2. Standard building life cycle stages from *Life Cycle Assessment of Buildings: A Practice Guid*e based on EN 15978 and ISO 21930 (Carbon Leadership Forum 2018).

The physical building scope was limited to core and shell (structure and enclosure) only. Interior fit-out and tenant improvements, i.e. interior finishes and interior partitions, were not included. The physical building scope is detailed in Table 2.

Table 2. LCA building scope

Category	Sub-category	Item	Material	CSI code	Comments / additional info
Structure	Gravity system	Beams and columns	Glulam (SPF)	061813	-
		Columns	Glulam (AYC)	061816	Exterior columns
		Slabs	CLT (SPF)	061719	5-Ply CLT, 6.6in thick
			GLT (SPF)	061813	GLT "ribs"
			Steel	051200	End rib connections
		Topping slab	Gypcrete	035319	2in Maxxon
		Acoustic underlayment	Gypcrete	090571	Maxxon
		Connections	Steel	051200	Just for glulam columns and beams
		Girders	Steel	051200	Steel box beams at atrium area Level 3
		Fireproofing paint	Intumescent paint	078123	1hr fire rating for steel girders. Class A flame spread FlameControl Paint in Concealed Spaces
	Lateral system	BRBs	Grout	051200	Cement grout fill
			Steel	051200	BRB incl. gusset plates.
		Shear walls	CLT (SPF)	061719	7-ply
	Foundation	Column footings	Concrete (4000 psi)	033130	-
			Rebar	032000	-
		Mat foundation	Concrete (4000 psi)	033140	-
			Rebar	032000	-
	Subgrade	Slab-on-grade	Concrete (3000 psi)	033030	-
			Rebar	032000	-
		Slab-on-grade underlayment	Crushed rock	312300	-
		Subgrade columns	Concrete (4000 psi)	033130	-
			Rebar	032000	-
		Subgrade walls and footings	Concrete (4000 psi)	033170	Partial basement
			Rebar	032000	-
		Suspended slabs	Concrete (5000 psi)	033800	PT-deck
			Rebar	032000	-
			PT steel	032000	-

Category	Sub-category	Item	Material	CSI code	Comments / additional info
Enclosure	Wall	Exterior glazing	Glazing	088000	Triple-pane
		Exterior mullions	Aluminum	084413	Storefront mullions
		Insulation	Mineral wool board	072100	3" mineral wool board, Rockwool Comfortboard 80
		Exterior wall	CLT (SPF)	074223	1. 3-ply (4.125in thick) CLT panels
		Air barrier	Polypropylene fabric with proprietary adhesive	072500	2. Self-Adhered Water Resistive Air Barrier: Vaproshield Wrap SA
		Insulated panel	Steel and insulation	072100	3. Kingspan Karrier Panel
		Carrier rails	Aluminum	072100	4. Karrier horizontal aluminum hat channel
		Hat channels	Galvanized steel	074229	5. Terracotta vertical rail support
		Finish	Terra cotta	074229	Rainscreen with support fastening system
			Prefinished steel panel	074213	Prefinished steel
			Modified wood finish	097200	Accoya Acetylated Wood
	Roof	Roof CLT	CLT (SPF)	074123	1. CLT roof structure. 5-ply
		Underlayment membrane	Modified bitumen membrane	075200	2. Self-adhered roofing underlayment membrane (WIP 300HT)
		Insulation build-up	Polyiso foam insulation	072200	3. Insulation build-up including tapered top (Hunter). 8"+taper
		Adhesive	Polyurethane	075423	4. Adhesive (Fast-Dual Cartridge)
			TPO membrane	075423	6. TPO adhesive (Sure-Weld)
		Rigid board	Glass mat gypsum panel	072113	5. USG Securerock rigid board
		Waterproofing	SBS membrane	075400	7. Originally TPO membrane (Carlisle Syntec), then replaced with 2-ply SBS
	Subgrade	Insulation	Extruded polystyrene	072113	2in rigid (R-10)
		Waterproofing	Geotextile	071700	Bentonite geotextile w/ integrated poly liner

As a summary, the LCA scope of the whole building LCA is captured by the LCA taxonomy in Table 3.

Table 3. LCA taxonomy scope description.

LCA taxonomy	Project information
Project information	
• Project name	Catalyst Building
• Project type	Office
• Project architect, engineer, and/or contractor	Katerra (Architect and Contractor), MGA Consulting Architect, KPFF Structural, McKinstry MEP
• Project owner, developer, and/or manager	Catalyst Spokane
• Project construction cost	N/A
• Rating scheme	None. Passive-House in practice with a net zero target.
• Rating achieved	According to McKinstry, the Catalyst Building is intended to be a zero-energy building (link), though the current, calculated EUI is not yet zero.
• Year of building construction completion	TBD 2020
• Year of building commissioning	TBD
• Year of occupancy	TBD 2020
• Year of refurbishment	Not applicable
Functional unit	
Building scale and performance	
Area characteristics	
• Building footprint area	Approximately 33,760 SF (3,138 m2)
• Total gross floor area (GFA)	168,805 SF (15,690 m2)
• Parking lot size	Not applicable
Height characteristics	
• Average ceiling height	14ft – 0in (office levels)
• Building total height	70ft – 0in
• Number of stories above grade	5
• Number of stories below grade	1 (for 1/2 of building due to sloped sight)
Relevant technical and functional requirements	
• Building use type(s)	Office, Educational
• Building occupancy type	(B) Business
• Design number of building occupants	2393. However, this does not reflect the increase in occupants at Level 3 (Eastern Washington University is adding classrooms).
• Design life expectancy in years	N/A
• Structural type (per IBC)	Mass Timber gravity and lateral systems. Type IV Heavy Timber.

LCA taxonomy	**Project information**
Geographic and site characteristics	
• Climate zone (per IECC)	IECC climate zone 5B (2015 International Energy Conservation Code 2016)
• Landscaping description	N/A
Location – address	
• Location - Street address	601 E. Riverside Avenue
• Location - city	Spokane
• Location - state/province	Washington
• Location - country	United States
Life cycle scope	
Reference study period (RSP)	N/A
Life cycle stages	• Life cycle stage A, which includes: ○ A1: Raw material extraction ○ A2: Transportation from material extraction site to manufacturing facility ○ A3: Manufacturing ○ A4: Transportation from manufacturing facility to building site ○ A5: Construction-installation process • Life cycle stage B: ○ B6: Operational energy use only • Life cycle stage D: ○ Biogenic carbon only
System boundary	
Building scope per Omniclass or RICS Professional Statement	See Table 2.

Methodology

This section details the analysis methodology for the LCA of 1) Katerra's CLT and 2) the Catalyst Building.

Life cycle assessment

LCA is a tool for evaluating the environmental aspects of a product throughout its entire life cycle. A product's life cycle stages may include raw material extraction, manufacturing/processing, usage, and disposal. LCA is generally based on the standards provided by ISO 14040 and ISO 14044 (ISO 2006a; ISO 2006b). Several required phases are included in the LCA model based on these standards: goal and scope definition, inventory analysis, impact assessment, and interpretation. These phases are diagrammed in Figure 3, which includes "Report Results" as a fifth phase.

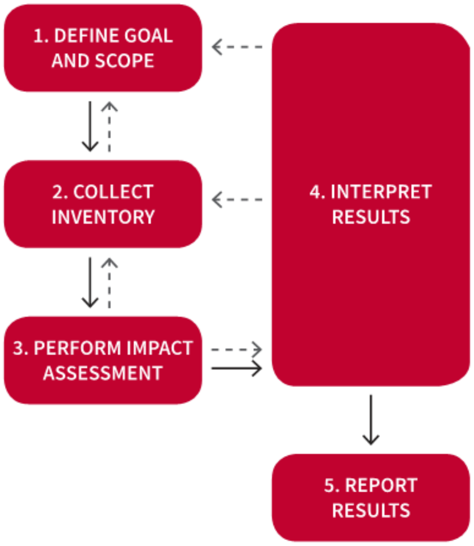


Figure 3. The four phases of a LCA from *Life Cycle Assessment of Buildings: A Practice Guide*, based on ISO 14040 (Carbon Leadership Forum 2018).

In general, an LCA takes into account the energy and material inputs and outputs over a production process and evaluates the impacts based on primary or secondary data. Primary data often involves first-hand data collection through surveys, observations, and experiments specifically designed for the context of the study. An example of primary data may include collecting the amount of electricity or water used to manufacture a product at the production facility.

CLT

This section describes the methods for data collection and analysis for the CLT supply chain and manufacturing process. The data used in this study included primary and secondary data. This section describes the source and types of data collected.

The CLT LCA analysis includes two main phases: lumber production and CLT manufacturing. Lumber production includes forestry operation and lumber manufacturing. Forestry operations include energy and fuel input associated with planting and harvesting.

Lumber production

Lumber used for CLT laminations manufacturing at the Katerra facility comes from Canadian sawmills and consists of a mix of spruce-pine-fire (SPF) wood species combination. The environmental impacts of lumber production were modeled based on a 2018 LCA report for surfaced dried softwood lumber published by the Athena Sustainable Materials Institute (Athena Sustainable Materials Institute 2018). Data associated with the raw material input, energy consumption, and transportation were based on the data described in the softwood lumber LCA and with the use of different life cycle inventory databases. Since the density of lumber directly affects the impacts of transportation, the impacts resulting from lumber transportation described in the Canadian lumber LCA were scaled using the wood density appropriate for the lumber used at the Katerra facility. All other factors remained unchanged. Table 4 shows the components of lumber production, the sources of the inventory data, and the regions they cover.

Table 4. Sources of inventory data for lumber production.

Component	Source	Region
Logs	USLCI, with transportation distance modified based on the Canadian lumber LCA (Laboratory 2012)	U.S. Northwest
Plastic Strap	2018 DATASMART LCI Package (LTS 2019)	North America
Steel Strap	Industry Data (worldsteel 2018)	Global
Packaging	2018 DATASMART LCI Package (LTS 2019)	North America
Electricity	Ecoinvent 3.5 (ecoinvent 2019)	Canada
Diesel	2018 DATASMART LCI Package (LTS 2019)	North America
Propane	2018 DATASMART LCI Package (LTS 2019)	North America
Natural Gas	2018 DATASMART LCI Package (LTS 2019)	North America
Hydraulic Fluid, lubricants, motor oil	2018 DATASMART LCI Package (LTS 2019)	North America
Waste	Ecoinvent 3.5 (ecoinvent 2019)	Global
Transportation	USLCI (Laboratory 2012)	North America

Data collection

Data associated with the production of CLT were collected through surveys, in-person discussions, and a factory site visit to Katerra's CLT manufacturing facility in Spokane Valley, WA. At startup, the facility is running at a lower capacity but is projected to quickly increase production. Thus, to account for future increased production capacity, data used in the analysis were based on the assumption of the facility running at 85% of its full capacity and produces 187,000 m^3 of CLT panels. Data collected included production capacity, manufacturing process, energy and material inputs, source of raw materials, logistics, and future production plans. Raw data were collected, organized, and computed for use in the LCA model. Additional data associated with transportation and production of materials such as resin and lumber were obtained from existing life cycle inventory databases. Figure 4 through Figure 8 contain photos taken onsite at the CLT manufacturing facility, showing the interior and assembly line operations inside the facility.

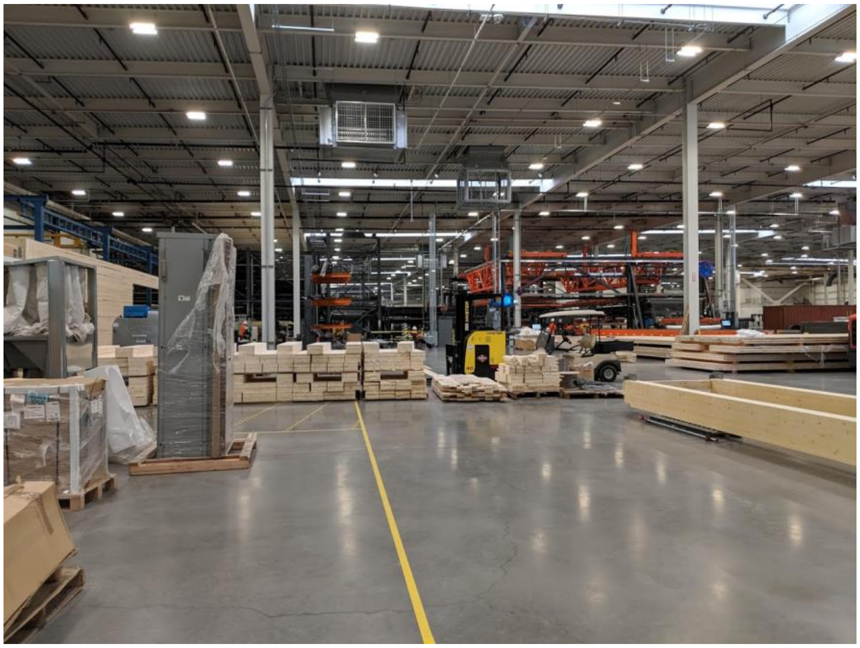


Figure 4. Interior of the manufacturing facility.

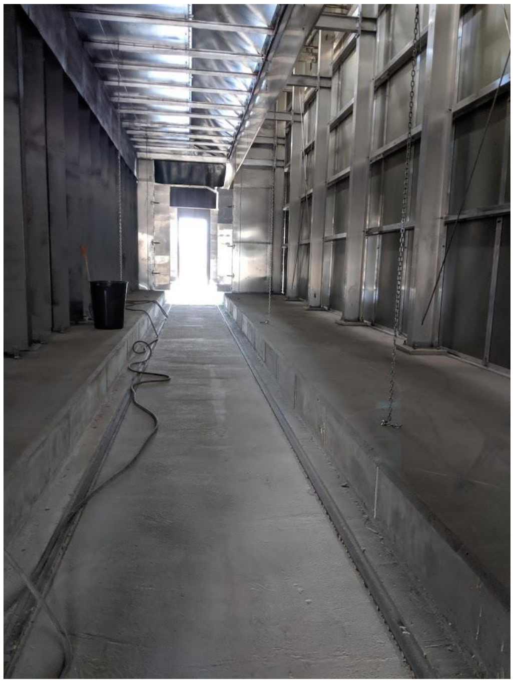


Figure 5. Interior of the kiln for lumber drying

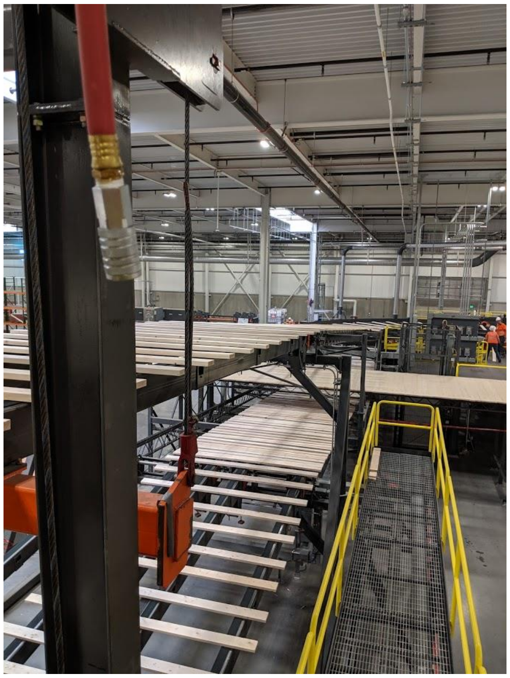


Figure 6. Lumber sorting line

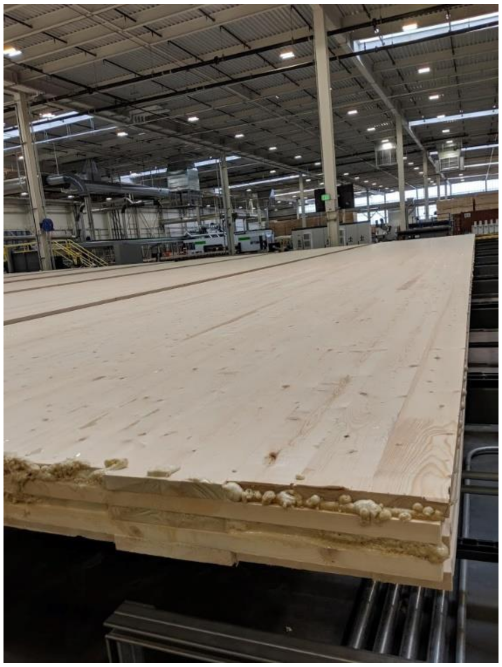


Figure 7. CLT panel after layup, glue application, and pressing

Figure 8. Finished panel packaging and transportation

Lumber inputs and delivery

The lumber used in the study comes from three different sawmills. One of the sawmills (Radium) provided 70% of the lumber, while the other two provided the remaining 30% of lumber. Rounded-edge lumber is purchased by the CLT manufacturing facility at the current stage. The average moisture content of the purchased lumber was assumed to be 19%. Depending on the moisture content of the purchased lumbers, the lumber is re-dried in the onsite kiln to 12±3% moisture content. Table 5 shows the lumber inputs to CLT manufacturing. The lumber infeed amount is based on the oven-dried weight.

Table 5. Lumber inputs. "tkm" = metric ton-kilometer. "odkg" = oven-dry kilogram

Component	Sawmill	Units	Quantity per m^3 of CLT
Lumber Infeed	-	m^3	1.19
	-	odkg	500
Lumber Delivery	Radium (70%)	tkm	148
	Elko (15%)	tkm	26
	Wynnwood (15%)	tkm	16

CLT manufacturing

CLT manufacturing involves several key phases, including lumber preparation, finger jointing, layup, and adhesive application, pressing, and panel finishing. Multiple steps are involved in each key process during manufacturing and each step requires inputs such as fuel and electricity. For example, lumber preparation involves lumber selection, drying, grouping, cutting, etc. and requires different equipment to kiln-dry and cut the lumber. Table 6 shows the amount of materials and co-products included in the declared unit of 1 m^3 of CLT panel. The mass of the CLT produced at the Katerra facility has a specific gravity (SG) of 0.42 on an oven-dry basis, giving the final product an oven-dry mass of 424.52 kg/m^3, including both the wood and resin portions. Co-products from the manufacturing processes, including shavings, trimmings, and sawdust, were estimated based on the amount of daily waste generation, which accounts for approximately 16% of every m^3 of CLT manufactured.

Table 6. Products and co-products associated with CLT manufacturing. "odkg" = oven-dry kilograms.

Category	Product	Units	Quantity per m^3 of CLT
Primary Product	CLT	m^3	1
		odkg	424.52
	Wood Portion	odkg	420
	Resin (Resin + Primer + Hardener)	kg	4.52
Co-Products		odkg	80
Total		kg	504.52

Resin input

Resin inputs depend on the thickness and number of plys of the CLT panel. Currently, 5-ply CLT panels with a finished thickness of 6.60 inches are being manufactured at the Katerra facility, and therefore, the numbers shown in Table 7 are based on the resin requirement for 5-ply panels. Two types of resins are used: Polyurethane (PUR) and Melamine Formaldehyde (MF). MF resin is used for finger jointing, and PUR is used for face-bonding applied during layup. MF resin (#4720) is manufactured in Oregon, while PUR resin (#HBX102) and primer are manufactured in Illinois.

Table 7. Resin inputs for CLT manufacturing.

Resin input	Units	Quantity per m^3 of CLT
Melamine Formaldehyde (MF) – finger joint	kg	0.72
Hardener – finger joint	kg	0.24
Polyurethane (PUR) – layup	kg	3.06
Primer - layup	kg	0.5
MF Transport	tkm	0.55
PUR Transport (Truck)	tkm	8.99
Primer Transport (Truck)	tkm	1.47

Energy Input

The main energy input for CLT manufacturing is electricity. An onsite kiln is operated using natural gas, while onsite transportation such as forklifts use propane and diesel fuel. All other machinery used for onsite CLT manufacturing are operated using electricity. The electricity inputs of the equipment were calculated based on the power and percent run time. For example, given that a finger joint score saw ran 100% of the time with a motor power of 7.46 kW, the hourly energy consumption for this equipment was calculated to be 6.34 kWh, assuming a 20-hour daily operation time at 85% mill capacity.

In this study, two models are considered:

1. **Baseline model.** The baseline model considers the processes and equipment that are known to be currently in operation at the CLT facility and does not account for equipment or processes that are possible additions for future CLT manufacturing
2. **Conservative model.** The conservative model accounts for all current and possible future additional equipment. The conservative model considers a "worst-case" scenario, meaning that a 100% machine run time is assumed for additional equipment that do not yet have a run time scheduled.

The total energy input involved in each of the manufacturing processes under the baseline model is shown in Table 8, and the energy input for the conservative model is shown in Table 9.

Table 8. The energy input for CLT manufacturing, baseline model.

Input	Unit	Quantity per m^3 of CLT
Lumber infeed	kWh	30.97
	m^3 of natural gas	2.6
Finger jointing	kWh	17.79
	kg of resin + hardener	0.96
Board sorting	kWh	17.64
Layup and adhesive application	kWh	1.15
	kg of resin + primer	3.56
	kg of primer	0.5
Pressing	kWh	2.52
Panel finishing	kWh	17.12

Table 9. Energy input for CLT manufacturing, conservative model.

Input	Unit	Quantity per m^3 of CLT
Lumber infeed	kWh	35.58
	m^3 of natural gas	2.6
Finger jointing	kWh	18.55
	kg of resin + hardener	0.96
Board sorting	kWh	30.2
Layup and adhesive application	kWh	1.15
	kg of resin + primer	3.56
	kg of primer	0.5
Pressing	kWh	6.19
Panel finishing	kWh	37.83

Life cycle impact assessment

Inventory analysis is performed by incorporating the collected data and can be analyzed using a range of software tools and models. For LCI analysis, SimaPro version 9 and the Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI) version 2.1 was used to model the environmental impacts from the processes associated with CLT production. TRACI is a method developed by the U.S. Environmental Protection Agency (EPA) to estimate the environmental impacts of a specific process system and is integrated in SimaPro (version 9). SimaPro is a software tool for modeling production and processing systems from a life-cycle perspective based on the system flow developed by the user. TRACI includes the five mandatory impact categories required for wood products in North America (FPInnovations 2015): global warming, acidification, eutrophication, smog formation, and ozone depletion. TRACI uses a number of impact indicators at different scales to present the level of impact from a product's life cycle. Although there are many available methods for inventory analysis, TRACI was selected because it is designed specifically for the U.S., which makes it consistent with the area of interest for this research. In addition, the Cumulative Energy Demand (CED) was used to calculate the primary energy consumption. The CED calculation was based on data published by Ecoinvent and was incorporated into SimaPro as an energy estimation method (Hischier et al. 2010; PRé 2019).

An LCA database contains measurements of material, energy, and environmental flows in and out of the production system for a defined amount of product. Existing LCA databases that are commonly used in

North America include the U.S. Life Cycle Inventory Database (USLCI). The USLCI was developed by the National Renewable Energy Laboratory (NREL) and contains individual accounting data of energy and material flows associated with many production systems. The ecoinvent database was also used.

Catalyst Building

This section discusses the material quantity data and LCA data for the LCA of the Catalyst Building. The LCA impacts for the Catalyst Building were calculated by 1) collecting material quantities, 2) collecting LCA data for the materials, and 3) multiplying the material quantities with the LCA data. Operational energy was also assessed separately.

Material quantities and LCA data

The CLF team provided a template (as an Excel file) to Katerra to fill in material quantities for the Catalyst Building. After receiving the material descriptions and quantities, the CLF team collected LCA data to match the materials used on the project. Some unit conversions were done in order to match the quantity units to the LCA data units. The final material quantities and LCA data selection are shown in Table 10.

The CLF team selected building LCA data primarily from the Athena Impact Estimator version 5.2, using life cycle stage A (A1-A5) impacts only. Athena was selected to be the primary source of LCA because it is a reputable source of LCA data specific to the building industry and North America. It is also free to use and was developed by the same organization that developed the softwood lumber data used in the study.

For some materials on the project, when a suitable material could not be found from the Athena database, a similar substitute material was used. This was sometimes an alternate material from Athena, sometimes from the Quartz database, which is an open-source, building-specific, North American LCA database, and sometimes from an environmental product declaration (EPD). The specific EPDs used in this study are shown in Table 10. When a suitable North American EPD could not be found, a European EPD was used. However, the European EPDs used the CML characterization methodology instead of TRACI 2.1, which meant that eutrophication and smog formation potential data could not be used because they had units that did not match TRACI 2.1. In these instances, the eutrophication and smog formation potential values were set to zero to avoid inflating the results in these categories. Some EPDs only covered A1 – A3 instead of A1 – A5. These discrepancies are also indicated in Table 10. It should be noted that these "less-than-ideal" data sources (those using CML methodology or having life cycle scope A1-A3) compromised only about 6% of the overall GWP impact of the building.

Table 10. Material quantities and LCA data sources for the Catalyst Building.

Category	Sub-category	Item	Material	Quantity	Units	LCA data source	LCA material name
Structure	Gravity system	Beams and columns	Glulam (SPF)	1593	m3	Athena	GluLam Sections
		Columns	Glulam (AYC)	33	m3	Athena	GluLam Sections
		Slab	CLT (SPF)	2291	m3	CINTRAFOR / Athena	Katerra CLT
			GLT (SPF)	573	m3	Athena	GluLam Sections
			Steel	23.9	tonnes	Athena	Steel Plate
		Topping slab	Gypcrete	534	m3	Athena (modified)	Lightweight concrete
		Acoustic underlayment	Gypcrete	10519	m2	Athena (modified)	Lightweight concrete
		Connections	Steel	22.8	tonnes	Athena	Steel Plate
		Girders	Steel	41.2	tonnes	Athena	Hollow Structural Steel
		Fireproofing paint	Intumescent paint	242	m2	EPD (CML, A1-A3 only)	Hensotherm Intumescent Paint* (Rudolf Hensel GmbH 2014)
	Lateral system	BRBs	Grout	4.3	tonnes	Athena	Portland Cement
			Steel	18.3	tonnes	Athena	Hollow Structural Steel
		Shear walls	CLT (SPF)	430	m3	CINTRAFOR / Athena	Katerra CLT
	Foundation	Column footings	Concrete (4000 psi)	95	m3	Athena	Concrete mix #3
			Rebar	4.2	tonnes	Athena	Rebar, Rod, Light Sections
		Mat foundation	Concrete (4000 psi)	471	m3	Athena	Concrete mix #3
			Rebar	23.0	tonnes	Athena	Rebar, Rod, Light Sections
	Sub-grade	Slab-on-grade	Concrete (3000 psi)	353	m3	Athena	Concrete mix #1
			Rebar	17.3	tonnes	Athena	Rebar, Rod, Light Sections

Category	Sub-category	Item	Material	Quantity	Units	LCA data source	LCA material name
		Slab-on-grade underlayment	Crushed rock	552	m3	Athena	Coarse Aggregate Crushed Stone
		Subgrade columns	Concrete (4000 psi)	20	m3	Athena	Concrete mix #2
			Rebar	2.4	tonnes	Athena	Rebar, Rod, Light Sections
		Subgrade walls and footings	Concrete (4000 psi)	285	m3	Athena	Concrete mix #3
			Rebar	20.5	tonnes	Athena	Rebar, Rod, Light Sections
		Suspended slabs	Concrete (5000 psi)	287	m3	Athena	Concrete mix #5
			Rebar	10.2	tonnes	Athena	Rebar, Rod, Light Sections
			PT steel	6.4	tonnes	Athena (modified)	PT steel
Enclosure	Wall	Exterior glazing	Glazing	2363	m2	Athena	Triple Glazed Soft Coated Air
		Exterior mullions	Aluminum	2.3	tonnes	Athena	Aluminum Window Frame
		Insulation	Mineral wool board	3383	m2	EPD (CML)	Rockwool® Stone Wool Insulation† (Rockwool North America 2019)
		Exterior wall	CLT (SPF)	3383	m2	CINTRAFOR / Athena	Katerra CLT
		Air barrier	Polypropylene fabric with proprietary adhesive	3383	m2	Athena	Polypropylene Scrim Kraft Vapour Retarder Cloth
		Insulated panel	Steel and proprietary insulation	3383	m2	EPD	Kingspan Quadcore Insulated Metal Panel (Kingspan 2019)
		Carrier rails	Aluminum	21.7	tonnes	Athena	Aluminum Extrusion
		Hat channels	Galvanized steel	14.3	tonnes	Athena	Galvanized Studs
		Finish	Terra cotta	2417	m2	Athena	Clay Tile
			Prefinished steel panel	1015	m2	Athena	Galvanized Sheet
			Modified wood finish	474	m2	EPD (CML, A1-A3 only)	Accoya® Modified Wood* (Accsys

Category	Sub-category	Item	Material	Quantity	Units	LCA data source	LCA material name
							Technologies PLC 2015)
	Roof	Roof CLT	CLT (SPF)	2956	m2	CINTRA-FOR / Athena	Katerra CLT
		Underlayment membrane	Modified bitumen membrane	2956	m2	Athena	Modified Bitumen membrane
		Insulation build-up	Polyiso foam insulation	2956	m2	Athena	Polyiso Foam Board (unfaced)
		Adhesive	Polyurethane	2956	m2	Quartz	Polyurethane flooring adhesive*
			TPO membrane	2956	m2	Athena	GAF Everguard© white TPO membrane 80 mil
		Rigid board	Glass mat gypsum panel	2956	m2	Athena	5/8" Glass Mat Gypsum Panel
		Waterproofing	SBS membrane	2956	m2	EPD	SBS-Modified Bitumen Roofing Membrane (Asphalt Roofing Manufacturers Association 2016)
	Sub-grade	Insulation	Extruded polystyrene	188	m3	Athena	Extruded Polystyrene
		Waterproofing	Geotextile	174	m2	Athena	6mil Polyethylene

* A4-A5 not covered

† Used CML characterization method, not TRACI 2.1

Out of the 47 materials considered in the building, only five used EPD data. By mass, only about 6% of the data was based on EPDs. By GWP contribution, 10% of the data was based on EPDs, most of it coming from the Kingspan steel insulated panel EPD.

Concrete LCA data were based on actual mix design submittals from the project. See the following subsection "Concrete" for more information.

The specific deviations from using generic Athena data are:

- **CLT**: The wood CLT data was provided by the CINTRAFOR team. Since the data extended only from A1-A4, the CLF team used Athena's data for Cross-Laminated Timber to fill in the data for A5.
- **Gypcrete**: The research team could not find an EPD for Maxxon gypcrete. Product spec sheets did not provide information about the compositional ratios. Therefore, gypcrete was approximated as Athena's Lightweight Concrete, modified to convert from Athena's "block" units to the volumetric units for gypcrete.
- **Intumescent paint**: Athena did not have an item for intumescent paint, and neither did Quartz. The CLF team found two EPDs for intumescent paint, one by Amonn® (J.F. Amonn Srl - Color Division Srl/GmbH 2019) and one by Rudolf Hensel GmbH (Rudolf Hensel GmbH 2014). Katerra did not specify a particular brand of intumescent paint, therefore the CLF team picked the EPD that had the slightly higher GWP value, which was the Rudolf Hensel brand (for the Amonn brand, the GWP for steel coating was 2.4 kg CO2e/kg paint, life cycle stages A1-A4, while for the Rudolf Hensel brand, the GWP was 2.5 kg CO2e/kg paint, life cycle stages A1-A3). The conversion from weight of paint to area of coverage was found from the Amonn EPD, which provided ranges of 200 – 1400 g paint/m2 of coverage (one as high as 4000), depending on the receiving surface. For this study, the conversion was approximated as 1 kg paint / m^2 of coverage.
- **PT steel**: Pre-stressing steel was approximated to have double the impacts of that of Athena's regular rebar. This is a reasonable assumption, given that EPDs for pre-stressing steel have GWP's ranging from 1.0 – 2.7 kg CO2e/kg steel (Hjulsbro Steel AB 2016; Ferrometall AS 2015).
- **Mineral wool board**: The specific product used on the project was Rockwool Comfortboard 80, which was a rigid mineral wool product. Athena had mineral wool ("MW"), which was assumed to be its most common form of batt insulation, but it had nothing specifically described as mineral wool board. Therefore, a Rockwool mineral wool board EPD was found and used to represent mineral wool board.
- **Insulated metal panel**: Athena had an insulated metal panel item in its database, but its GWP value was suspiciously large (orders of magnitude larger than that of the actual product used in the building), therefore an EPD for the actual product was used instead. Two EPDs for Kingspan

Karrier panels were available from the Kingspan Certifications website[1] – 1) an SIP panel, which had polyisocyanurate insulation and was described as being the more standard option, and 2) a Quadcore option, which seemed more technologically advanced. The Quadcore option was selected for this study because it had the slightly higher GWP value, making it a slightly more conservative choice.

- **Modified wood finish**: The modified wood finish/cladding used in the building was Accoya Acetylated Wood. There was no matching item for this in Athena, but there was an EPD for the specific product (Accsys Technologies PLC 2015). However, this EPD presented negative GWP values, which was inconsistent with TRACI and Athena's methodology for representing GWP of biogenic carbon. Therefore, a separate Accoya cradle-to-gate carbon footprint LCA report was consulted for non-negative GWP values (Trueman 2012). Both sources provided results for multiple wood species, but the wood species did not overlap between the two sources. In the end, the GWP impact was based on "Alder U.S." from the LCA report, and all the other impacts were based on "Radiata Pine" from the EPD (since the EPD did not have "Alder U.S.").
- **Polyurethane**: For the roofing adhesive, the building used Carlisle Syntec's FAST Dual Cartridge, which is a two-component polyurethane adhesive. Athena did not have a polyurethane product or an adhesive product in its database. Quartz did have "polyurethane flooring adhesive," so its data was used. The conversion from square meters (quantity measured) to kg (LCA data) was performed using information from the Carlisle product spec sheet (Carlisle Syntec Systems 2018).
- **SBS membrane:** Athena did not have any SBS membranes in its database. It did have "modified bitumen membrane," which is similar to an SBS-modified bitumen membrane. However, the impacts in Athena were given per kg of product, which would have required making assumptions about quantity of product used per unit area. Therefore, it was deemed more expedient and representative to use the industry-average EPD for SBS-Modified Bitumen Roofing Membrane published by the Asphalt Roofing Manufacturer's Association (Asphalt Roofing Manufacturers Association 2016), which provided the impacts in the same units as the material quantities (square meters).

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[1] https://www.kingspan.com/us/en-us/about-kingspan/kingspan-insulated-panels/certifications

After the material quantities and LCA impact data selection were finalized, the material quantities were multiplied with the LCA impact data to produce the overall building LCA impacts. The results were then divided by the gross internal floor area of the building (15,690 m^2) in order to normalize the impacts per unit area, as is common in building LCAs. The results are presented in the "Results" section.

Concrete

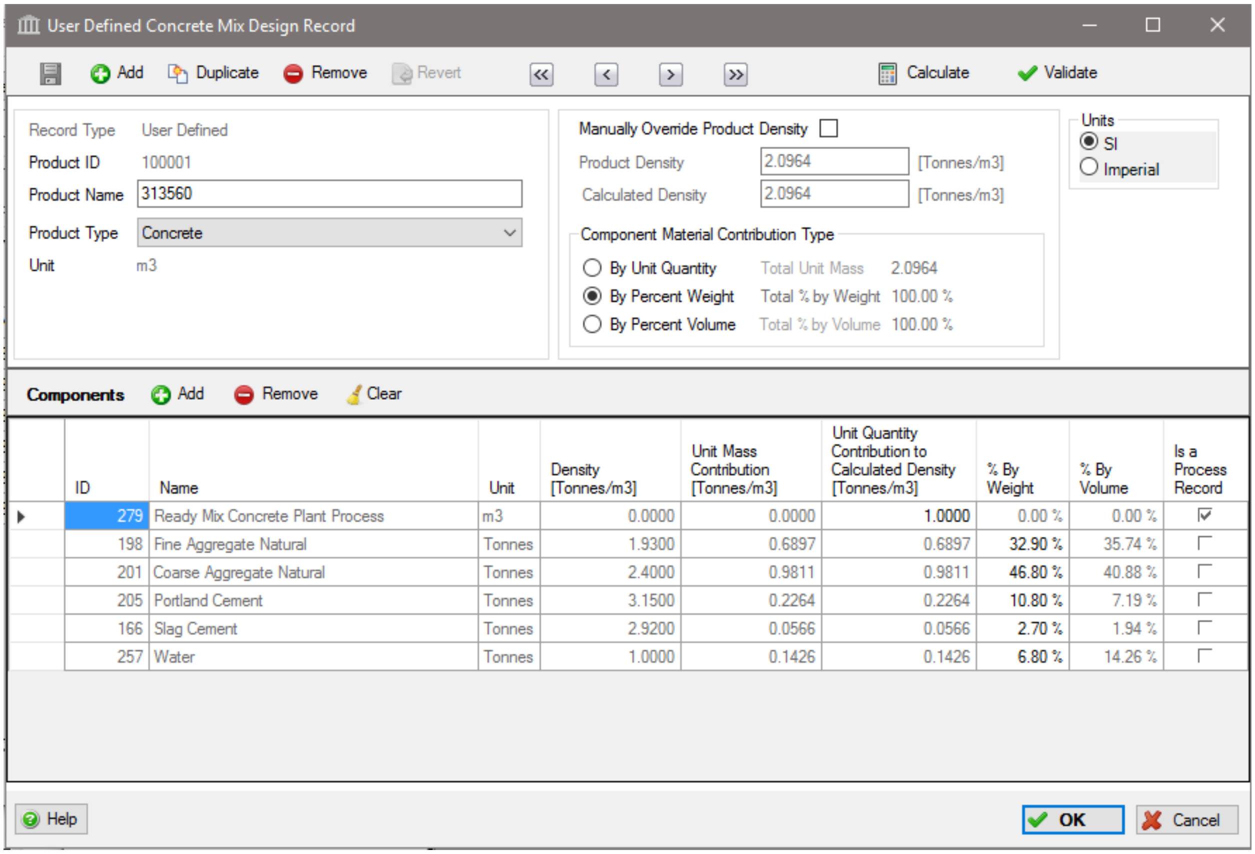
Katerra was able to provide concrete mix submittals from the actual project. A description of these mix designs from the submittals is shown in Table 11. The mixes are numbered 1 – 6 here for simplicity, and correspond to the concrete mix designs in Table 10. Since the mix designs were not categorized in exactly the same way as the concrete quantity data, the research team made some assumptions in assigning the mix designs to the concrete quantity data. In cases where there was some uncertainty, the research team selected the more conservative (higher GWP) mix design option for the building component. The building components assumed for each mix design is shown in Table 11. As a result of these assumptions, two mix designs were not used in this analysis.

Table 11. Concrete mix design descriptions from project submittals and assumed building component.

Concrete mix #	Mix Code	Mix Description	Mix Usage	Building component	Design concrete strength
1	313560	3500 PSI 3/ 4"	INTERIOR MISC INTERIOR CONCRETE & NON-EXPOSED INTERIOR SLABS ON GRADE	Slab-on-grade	3000 psi
2	314060	4000 PSI 3/ 4"	INTERIOR COLUMNS & SHEAR WALLS	Subgrade columns	4000 psi
3	314066	4000 PSI 3/ 4"	EXTERIOR BASEMENT WALLS, SPREAD FOOTINGS, MAT FOUNDATIONS, EXTERIOR SLABS ON GRADE, SITE WALLS & MISC. EXTERIOR CONCRETE	Mat foundation	4000 psi
4	315060	5000 PSI 3/ 4"	INTERIOR MILD REINFORCED SLABS AND BEAMS	Not assigned (N/A)	N/A
5	320250	5000 PSI 3/ 4"	INTERIOR, WRA, HRWRA P/ T SLALS AND BEAMS	Suspended slabs	5000 psi
6	315061	5000 PSI 3/ 4"	INTERIOR SRA EXPOSED INTERIOR SLABS ON GRADE	N/A	N/A

These mix designs were entered into Athena's custom concrete mix design module (the "User Defined Concrete Mix Design Library"), using the percentage contributions from each material by weight. The admixtures were ignored because they were a negligible percentage of the overall mass and because

Athena did not have LCA data for admixtures. A sample screenshot of the mix design data entry is shown in Figure 9.



Record Type: User Defined
Product ID: 100001
Product Name: 313560
Product Type: Concrete
Unit: m3

Manually Override Product Density ☐
Product Density: 2.0964 [Tonnes/m3]
Calculated Density: 2.0964 [Tonnes/m3]

Component Material Contribution Type
○ By Unit Quantity — Total Unit Mass 2.0964
● By Percent Weight — Total % by Weight 100.00 %
○ By Percent Volume — Total % by Volume 100.00 %

Units
● SI
○ Imperial

ID	Name	Unit	Density [Tonnes/m3]	Unit Mass Contribution [Tonnes/m3]	Unit Quantity Contribution to Calculated Density [Tonnes/m3]	% By Weight	% By Volume	Is a Process Record
279	Ready Mix Concrete Plant Process	m3	0.0000	0.0000	1.0000	0.00 %	0.00 %	☑
198	Fine Aggregate Natural	Tonnes	1.9300	0.6897	0.6897	32.90 %	35.74 %	☐
201	Coarse Aggregate Natural	Tonnes	2.4000	0.9811	0.9811	46.80 %	40.88 %	☐
205	Portland Cement	Tonnes	3.1500	0.2264	0.2264	10.80 %	7.19 %	☐
166	Slag Cement	Tonnes	2.9200	0.0566	0.0566	2.70 %	1.94 %	☐
257	Water	Tonnes	1.0000	0.1426	0.1426	6.80 %	14.26 %	☐

Figure 9. Sample mix design data entry into Athena's Concrete Mix Design module.

These percentage contributions in each of the mixes are summarized in Table 12, along with the weight per cubic meter and the global warming potential result from Athena.

Table 12. Concrete mix percentages by weight, total density, and resulting GWP from Athena's concrete mix design tool.

#	Concrete mix percentage contributions by weight						Concrete density (tonnes/m^3)	GWP (kg CO2e/m^3)
	Cement	Slag	Fine aggregate	Coarse aggregate	Water	Grand total		
1	10.8%	2.7%	32.9%	46.8%	6.8%	100%	1.79	259
2	11.7%	2.9%	32.3%	46.5%	6.6%	100%	1.80	281
3	13.1%	3.2%	26.7%	49.7%	7.2%	100%	1.61	315
4	13.5%	2.4%	31.1%	46.8%	6.3%	100%	1.81	322
5	13.9%	2.5%	31.7%	45.5%	6.4%	100%	1.81	330
6	13.5%	2.3%	31.5%	46.4%	6.2%	100%	1.82	322

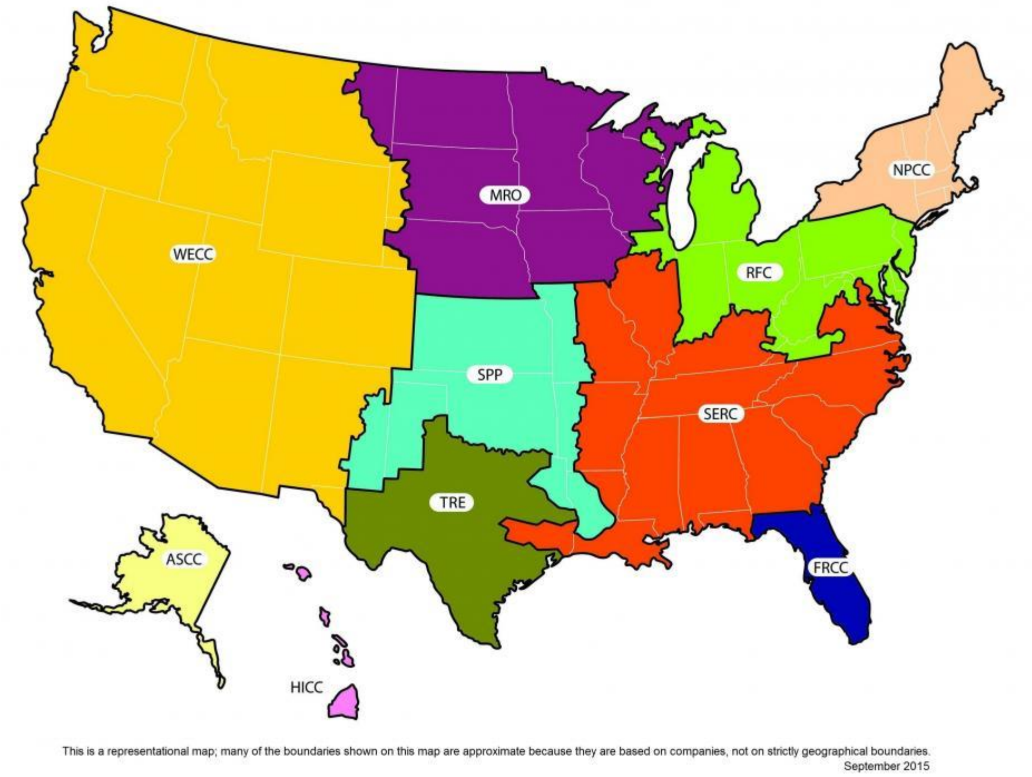
Generally, the GWP impacts from the actual concrete mix designs were lower than that of Athena's regional Seattle concrete data. The Athena values for concrete strengths of 3000 – 5000 psi ranged from 335 – 507 kg CO2e/m3, while the Catalyst concrete mixes ranged from 295 - 370 kg CO2e/m3.

Operational energy

The energy use intensity (EUI) for the final design of the building was provided by McKinstry as 22.4 kBTU/sf/year. The only mode of energy consumption was electricity; there were no other sources of energy for this building (e.g. no gas, no renewable energy).

eGrid2010 (US EPA 2010) was used to estimate the GWP of electricity consumption for this building. Although a more recent of eGrid (version 2016) was available, the 2010 version was selected for this analysis in order to be consistent with the CLT analysis, which used the latest available version of eGrid (version 2010) from SimaPro.

The Western Electricity Coordinating Council (WECC) region of the North American Electric Reliability Corporation (NERC) region map was selected. See Figure 10 for a map of the NERC regions.



This is a representational map; many of the boundaries shown on this map are approximate because they are based on companies, not on strictly geographical boundaries.
September 2015

Figure 10. NERC regions used in eGrid (US EPA 2010).

The CO2e emission rate for the WECC region in eGRID2010 in SimaPro was slightly different than the value provided on the US EPA website. This was likely because SimaPro included additional factors such as transportation and additional greenhouse gases. Since the SimaPro value was higher and thus slightly more conservative, this analysis used the SimaPro value, which was 0.552 kg CO2e/kWh.

The building EUI was combined with this emission rate to obtain the GWP impact per year for this building:

$$= \left(22.4\,\frac{kBTU}{sf \cdot yr}\right)\left(\frac{3.28^2 sf}{m^2}\right)\left(\frac{1\ kWh}{3.412\ kBTU}\right)\left(\frac{0.552\ kg\ CO2e}{kWh}\right)$$

= 39.0 kg CO2e/m2/year

The total GWP impact over a 60 year building lifespan was calculated as:

= (39.0 kg CO2e/m2/year) x (60 years)

= 2,339 kg CO2e/m2

Results

The results of the CLT LCA and the Catalyst Building LCA are presented in this section.

CLT

The results of the CLT LCA are presented separately for the baseline model and the conservative model.

Baseline model

Table 13 shows the impacts of each process involved in the CLT production: lumber production, lumber transportation, CLT manufacturing, and CLT transportation to the construction site. The total global warming was 129.62 kg CO2e for the CLT, with onsite CLT manufacturing being the largest contributor, producing 59.43 kg CO2e to the total. Figure 11 describes the percent contribution of each process.

Table 13. LCA Impacts and primary energy consumption of each process included in the CLT LCA under baseline model (unit: 1 m3 of CLT).

Measurement	Unit	Total	Lumber Production	Lumber Transport	Onsite CLT Manufacturing
Global Warming	kg CO_2e	129.62	51.40	18.79	59.43
Acidification	kg SO_2e	1.22	0.53	0.24	0.45
Eutrophication	kg Ne	0.1	0.03	0.01	0.05
Smog	kg O_3e	20.31	10.52	6.18	3.61
Ozone Depletion	kg CFC-11e	4.08E-06	1.63E-06	7.94E-10	2.45E-06
Non-renewable, Fossil	MJ	2,359.05	828.84	286.13	1,244.08
Non-renewable, Nuclear	MJ	242.8	79.31	-	163.49
Non-renewable, Biomass	MJ	0.0019	-	-	0.0019
Renewable, Biomass	MJ	1,563.61	1,562.01	-	1.60
Renewable, Wind, Solar, Geothermal	MJ	74.75	73.91	-	0.84
Renewable, Water	MJ	4.12	-	-	4.12

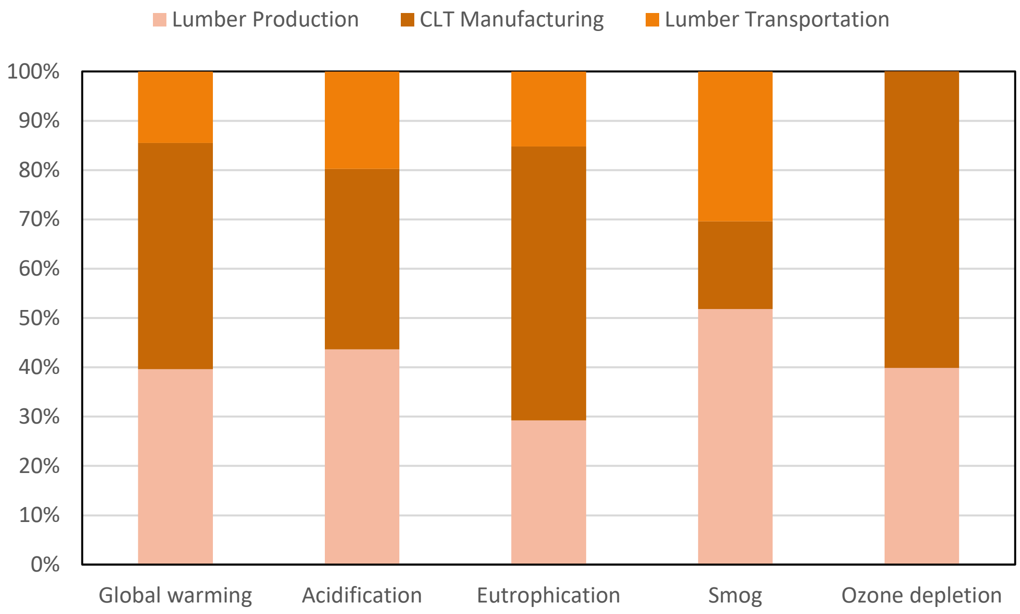


Figure 11. Contribution of each supply chain process, baseline model.

Conservative model

In comparison to the baseline model, the CLT manufacturing contributed higher impacts to the overall impacts of the supply chain. Out of a total of 157.52 kg CO2e in global warming contribution, onsite CLT manufacturing contributed 87.32 kg CO2e By accounting for all possible future equipment and assuming all additional equipment operate 100% of the time, onsite CLT manufacturing contributed 32% higher impacts compared to the baseline model. The conservative model showed a 22% increase in total impacts compared to the baseline model. Table 14 describes the percent contribution of each process. Figure 12 demonstrates the percent contribution of each process in the supply chain.

Table 14. LCA Impacts and primary energy consumption of each process included in the CLT LCA under conservative model (unit: 1 m3 of CLT).

	Unit	Total	Lumber Production	Lumber Transport	Onsite CLT Manufacturing
Global Warming	kg CO_2e	157.52	51.40	18.79	87.32
Acidification	kg SO_2e	1.45	0.53	0.24	0.67
Eutrophication	kg Ne	0.1	0.03	0.01	0.06
Smog	kg O_3e	21.64	10.52	6.18	4.94
Ozone Depletion	kg CFC-11e	4.08E-06	1.63E-06	7.94E-10	2.45E-06
Non-renewable, Fossil	MJ	2,786.72	828.84	286.13	1671.75
Non-renewable, Nuclear	MJ	242.8	79.31	-	163.49
Non-renewable, Biomass	MJ	0.0019	-	-	0.0019
Renewable, Biomass	MJ	1,563.61	1,562.01	-	1.60
Renewable, Wind, Solar, Geothermal	MJ	74.75	73.91	-	0.84
Renewable, Water	MJ	4.12	-	-	4.12

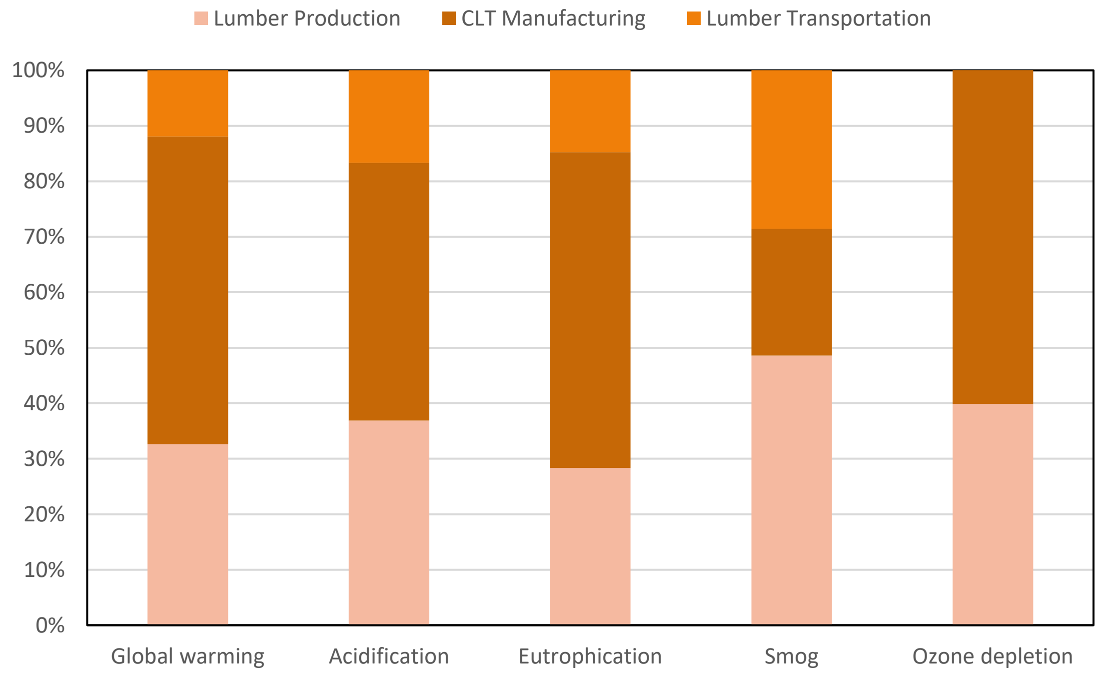


Figure 12. Contribution of each supply chain process, conservative model.

A study conducted by CORRIM (Puettmann et al. 2017) showed a global warming impact of 82.91 kg CO2e for onsite CLT manufacturing, which is higher than the results shown in the baseline model, but slightly lower than that of the conservative model. The lumber transportation in the CORRIM study had a total of 96.85 kg CO2e if lumber transportation is added to the onsite CLT manufacturing, higher than the results under the baseline model. Further, if lumber production was included, the overall global warming impact in the CORRIM study was 158.67 kg CO2e, similar to the result under the conservative model shown here. Another study by Chen et al. demonstrated a global warming impact of 96.71 kg CO2e for onsite CLT manufacturing, which was higher than both of the models described in this report (Chen et al. 2019). However, that study considered different lumber transportation scenarios: if the lumber was produced locally, the total global warming impact of onsite CLT manufacturing and lumber transportation was 98.1 kg CO2e, which is lower than the global warming impact reported under the conservative model. It is also important to note the wood species used for lumber production, which would directly influence the impacts of transportation. Chen et al. considered a baseline scenario using a 50-50 mix of Douglas-fir and Western Hemlock for lumber, while CORRIM used Douglas-fir only. On the other hand, Katerra uses SPF lumber, which has a lower SG than Douglas-fir and Western Hemlock.

Contribution analysis

A contribution analysis was performed to investigate the impact of each sub-process within a supply chain stage. Lumber production is divided into three sub-processes, including forestry operation, log transportation to lumber mills, and lumber manufacturing. Onsite CLT manufacturing is divided into six sub-processes, including lumber infeed, finger joint, board sorting, layup, and adhesive application, press, and panel finishing. Contribution of the onsite CLT manufacturing varied between the baseline and conservative models, whereas the contribution of all other processes remained unchanged since the different models only apply to CLT manufacturing (Figure 13). Figure 14 shows the global warming contribution of each sub-process in the onsite CLT manufacturing stage for both the baseline model and conservative model. The main global warming contribution came from the lumber infeed, which included drying of the lumber in preparation for finger joint. When considering the conservative model, the contribution of the panel finishing sub-process significantly increased compared to that of the baseline model. This could be due to the extra processing equipment that is expected to be added in the future, as well as extra dust collection system that may be required in the future.

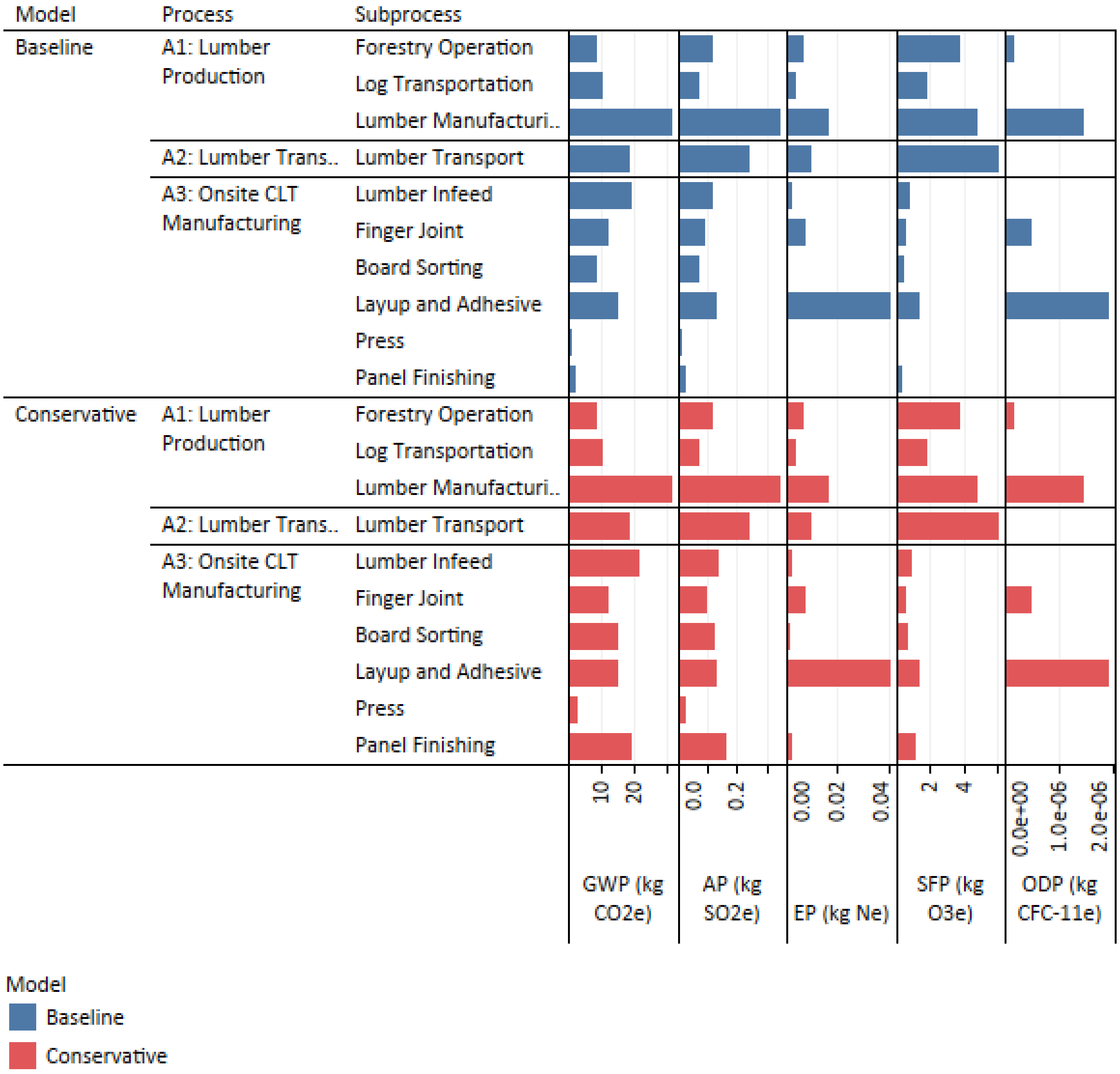


Figure 13. Contribution of each process in the two CLT LCA models.

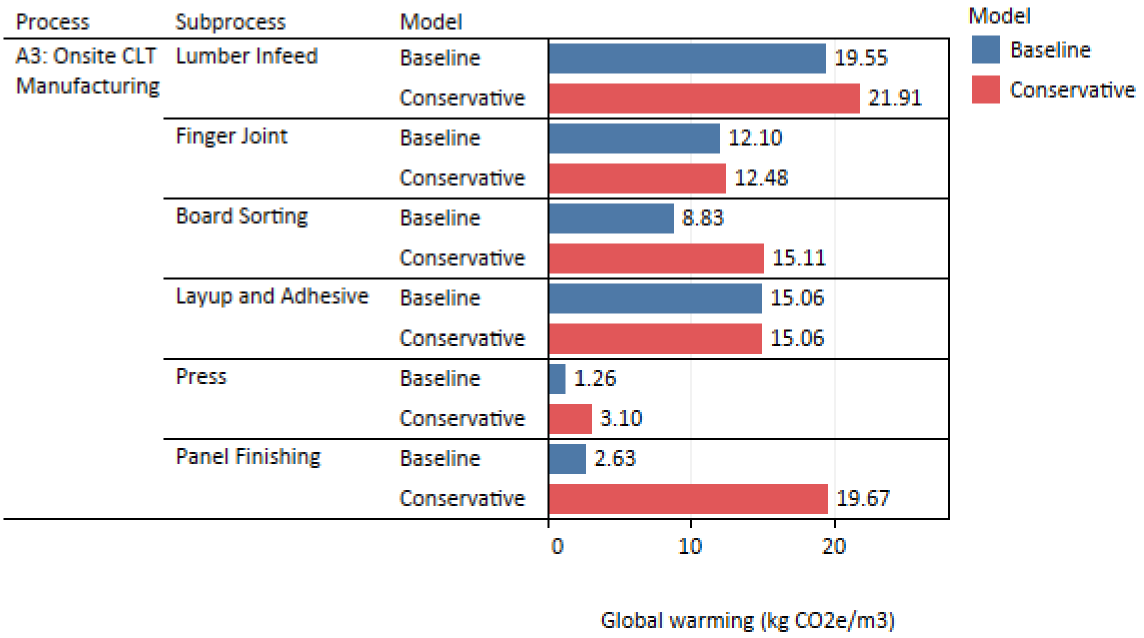


Figure 14. Side-by-side comparison of onsite CLT manufacturing between the baseline and conservative models.

Catalyst Building

This subsection presents the LCA results for the Catalyst Building, starting with an overview of all impact categories before diving into a more detailed analysis of GWP. This subsection focuses mostly on the life cycle stage A results because it had the most comprehensive information in terms of material quantities and LCA data. In order to flesh out stage B or stage C impacts, more information about maintenance, material replacement rates, disposal plans, etc. would have been needed.

For ease of interpretation, similar materials were grouped together for color-coding of materials. The material grouping scheme is shown in Table 15.

Table 15. Material grouping for graph color-coding.

Material group	Material (original name)
Aluminum	Aluminum
Concrete	Concrete (3000 psi)
	Concrete (4000 psi)
	Concrete (5000 psi)
	Gypcrete
Crushed rock	Crushed rock
Extruded polystyrene	Extruded polystyrene
Glass mat gypsum panel	Glass mat gypsum panel
Glazing	Glazing
Grout	Grout
Intumescent paint	Intumescent paint
Mineral wool board	Mineral wool board
Polyiso foam insulation	Polyiso foam insulation
Polyurethane	Polyurethane
Steel	Galvanized steel
	Prefinished steel panel
	PT steel
	Rebar
	Steel
Steel insulated panel	Steel and insulation
Terra cotta	Terra cotta
Textiles and membranes	Geotextile
	Modified bitumen membrane
	Polypropylene & adhesive
	SBS membrane
	TPO membrane
Wood	CLT (SPF)
	GLT (SPF)
	Glulam (AYC)
	Glulam (SPF)
	Modified wood finish

All impact categories, life cycle stage A

Figure 15 presents an overview of all the impact categories and their distribution by material groups. Figure 16 presents a breakdown of all impact categories by building category, subcategory, and item. These figures present an overview of how the distribution of impacts by material groups and items vary by impact category. For example, it is interesting to note that the proportion of overall impact attributed to wood is smaller in GWP than in primary energy, or that concrete has a relatively large impact in GWP and EP but has a less significant impact in the other categories. Note that ODP tends to have a very high level of uncertainty, which could explain why its distribution pattern differs from the other impact categories.

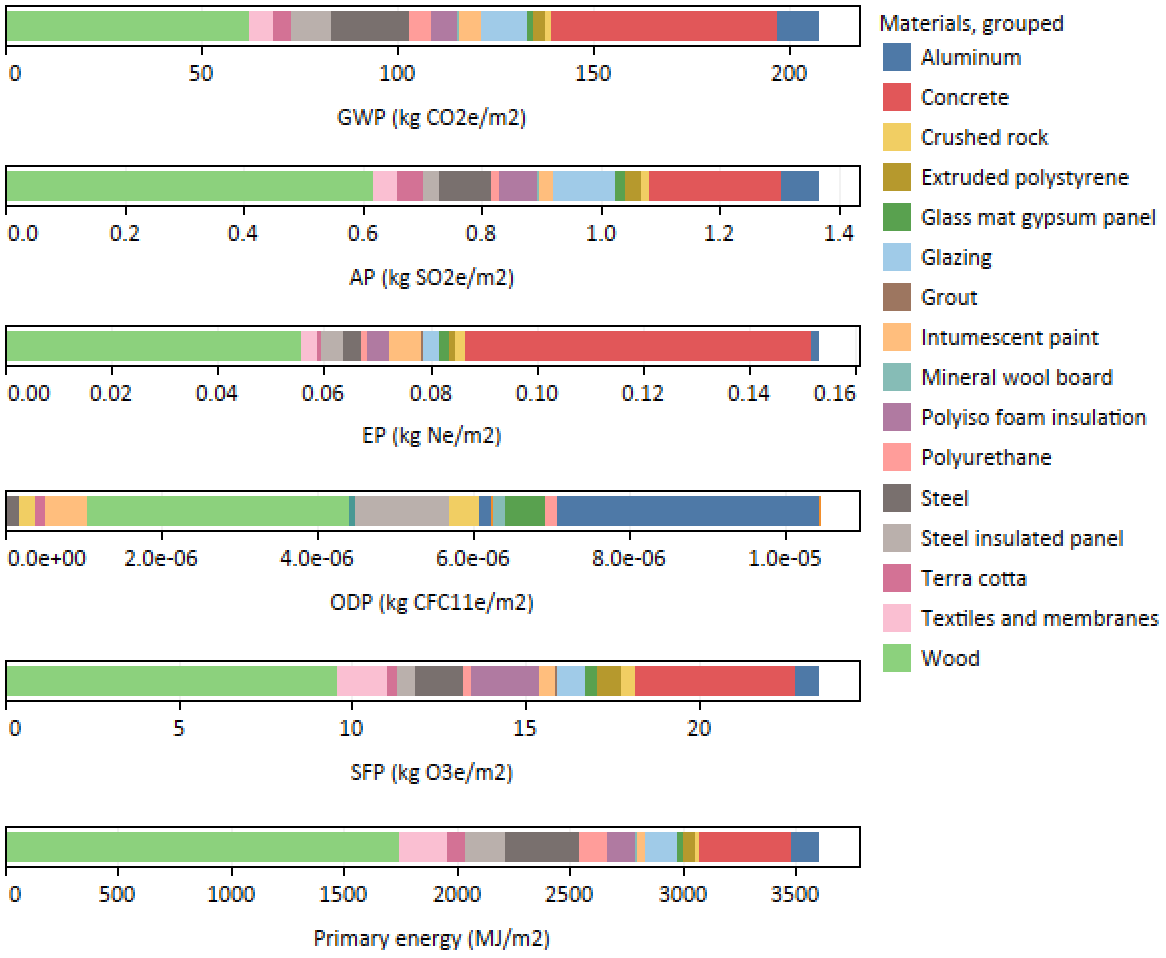


Figure 15. Overview of all impact category results, life cycle stage A only, color-coded by material group.

Figure 16. All impact categories by building category, subcategory, and item, life cycle stage A.

GWP detailed results, life cycle stage A

Figure 17 presents the relative contributions of the materials to the overall GWP, separated by category and subcategory. This figure shows that:

- The GWP of structure is greater than that of enclosure
    - In the structural system, the gravity system has the greatest proportion of impacts, followed by subgrade, foundation, then lateral system
    - In the enclosure, the wall system has the greatest proportion of impacts, followed by roof then subgrade.
- In terms of materials, wood, concrete, aluminum and glazing have the greatest GWP. This is explored in later figures.

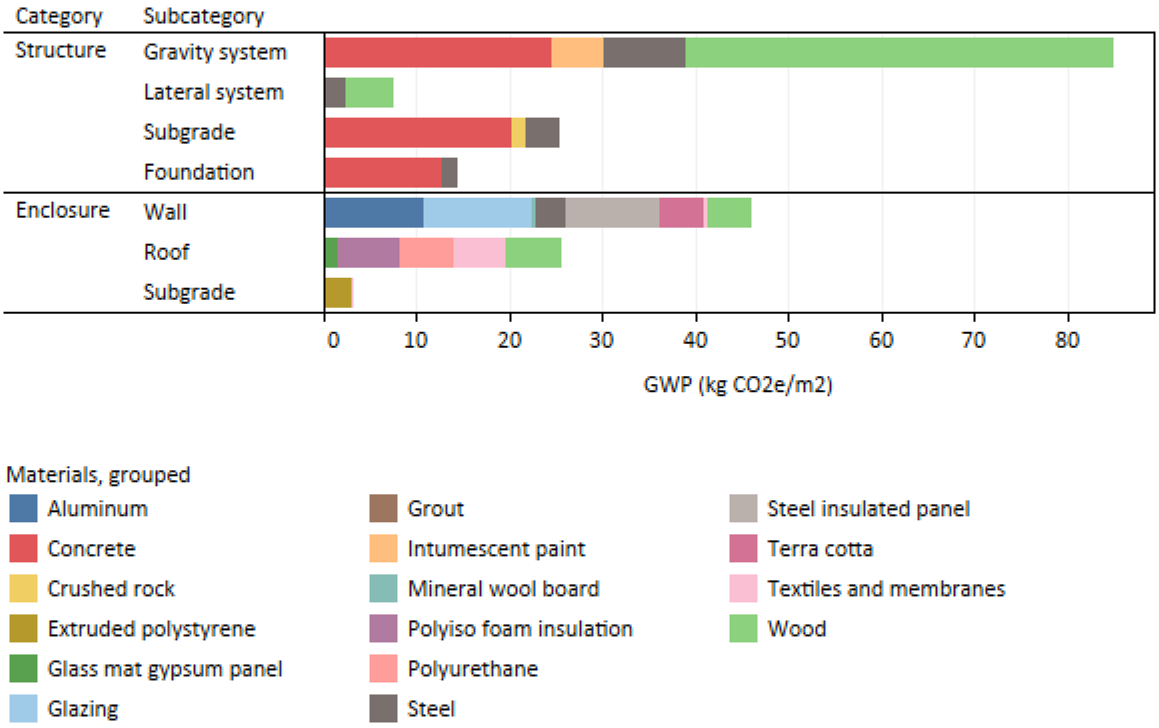


Figure 17. GWP results (life cycle stage A), separated by category, subcategory, and color-coded by material group.

Figure 18 separates the results by item.

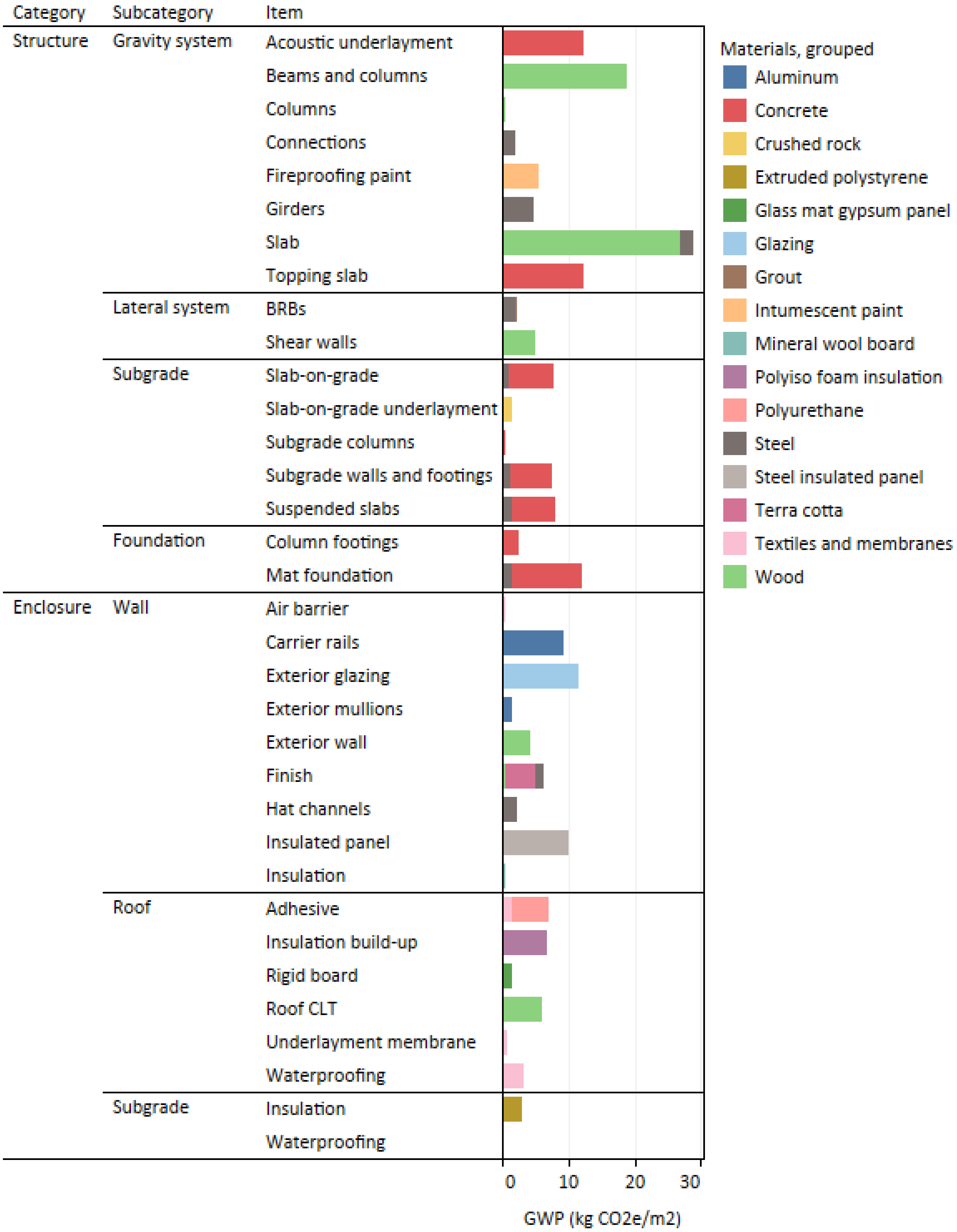


Figure 18. GWP results (life cycle stage A), separated by category, subcategory, item, and color-coded by the material groups.

Figure 19 ranks the overall impacts individual materials on the project by descending GWP impact, color-coded by the material groups. As seen in previous figures, CLT has the greatest overall impact, followed by aluminum, gypcrete, and concrete.

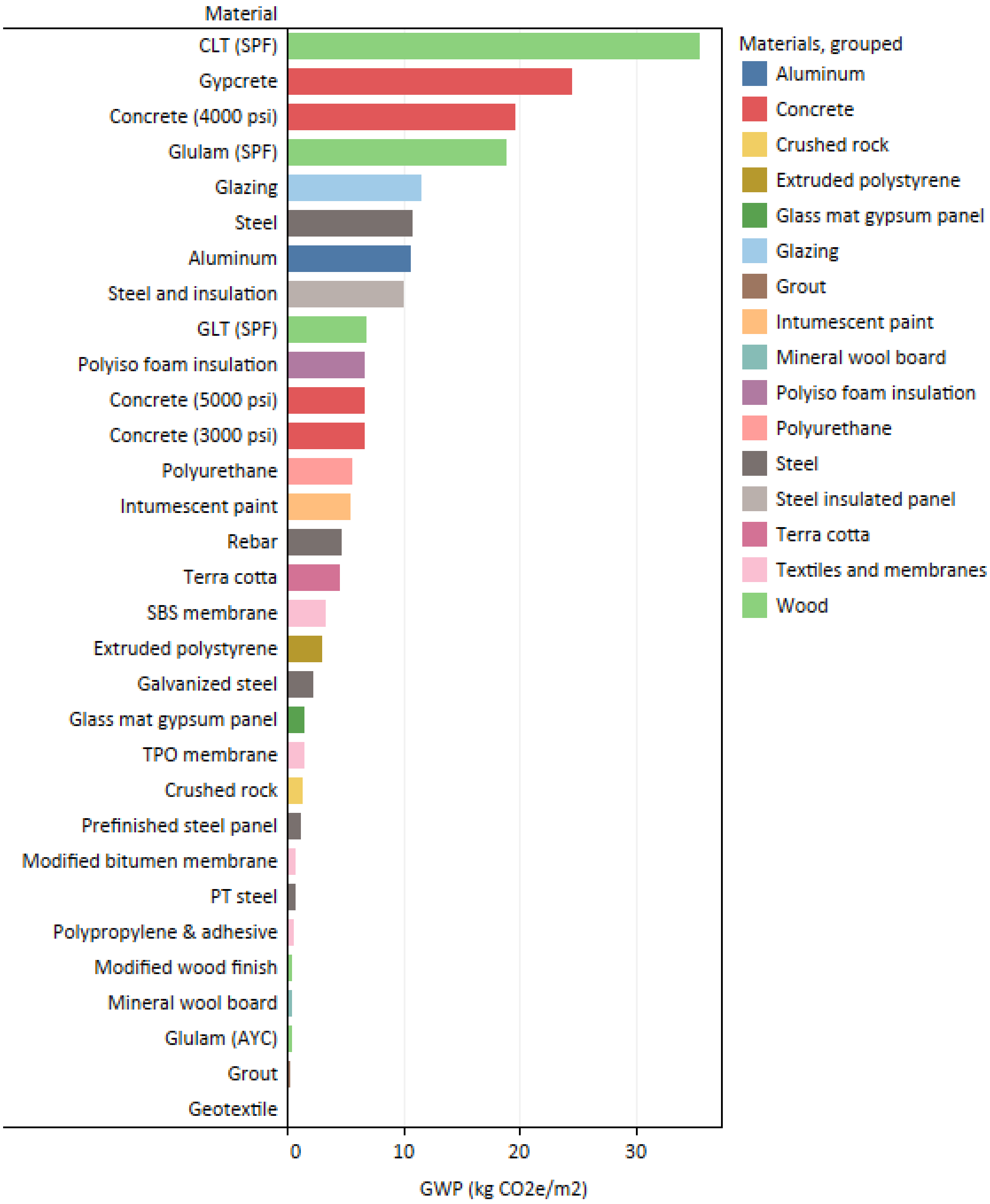


Figure 19. GWP results (life cycle stage A), ranked by the overall impact of materials, color-coded by the material groups.

Figure 20 ranks the overall impact of the material groups by descending GWP impact. As seen earlier, wood and concrete are the most significant, and have a similar overall GWP impacts. Steel, glazing, aluminum, and steel insulated panels are also significant.

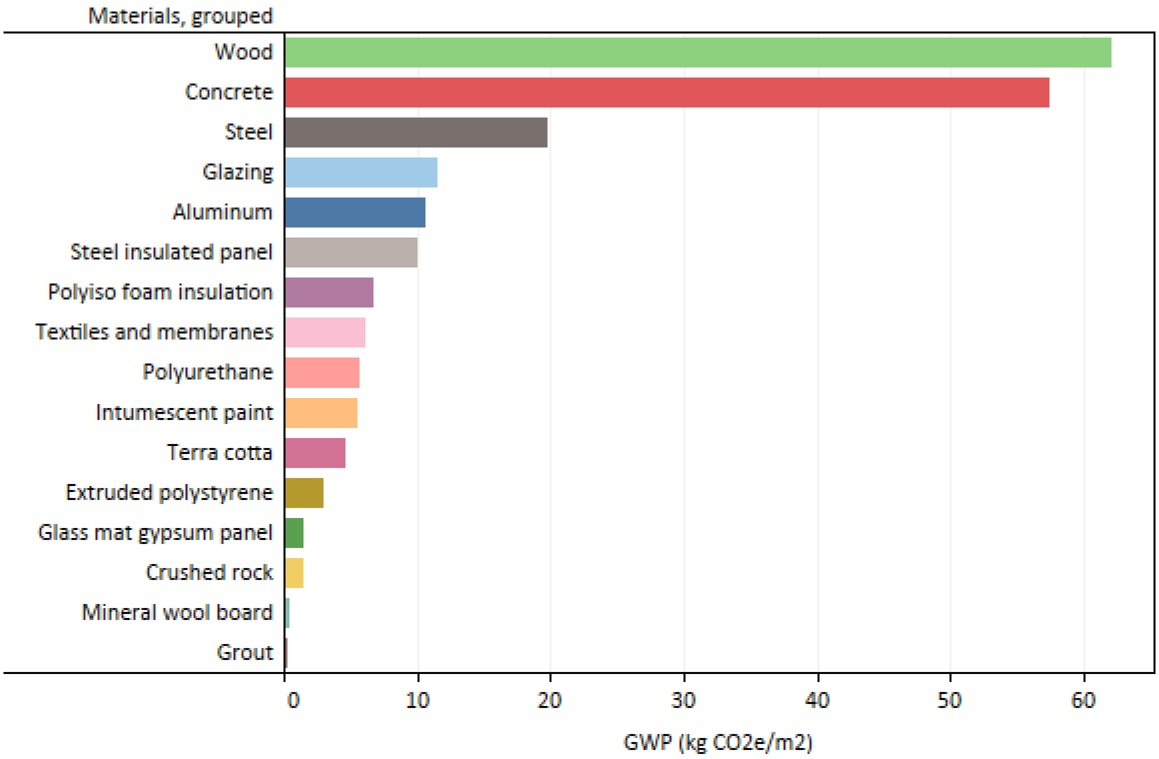


Figure 20. GWP results (life cycle stage A), ranked by the overall impact of material groups.

Figure 21 presents an alternative method of viewing the material contributions to overall GWP using a treemap. The size of the rectangles represent the magnitude of the GWP contribution, and the color-coding indicates material group. Not all rectangles could be labeled due to space constraints.

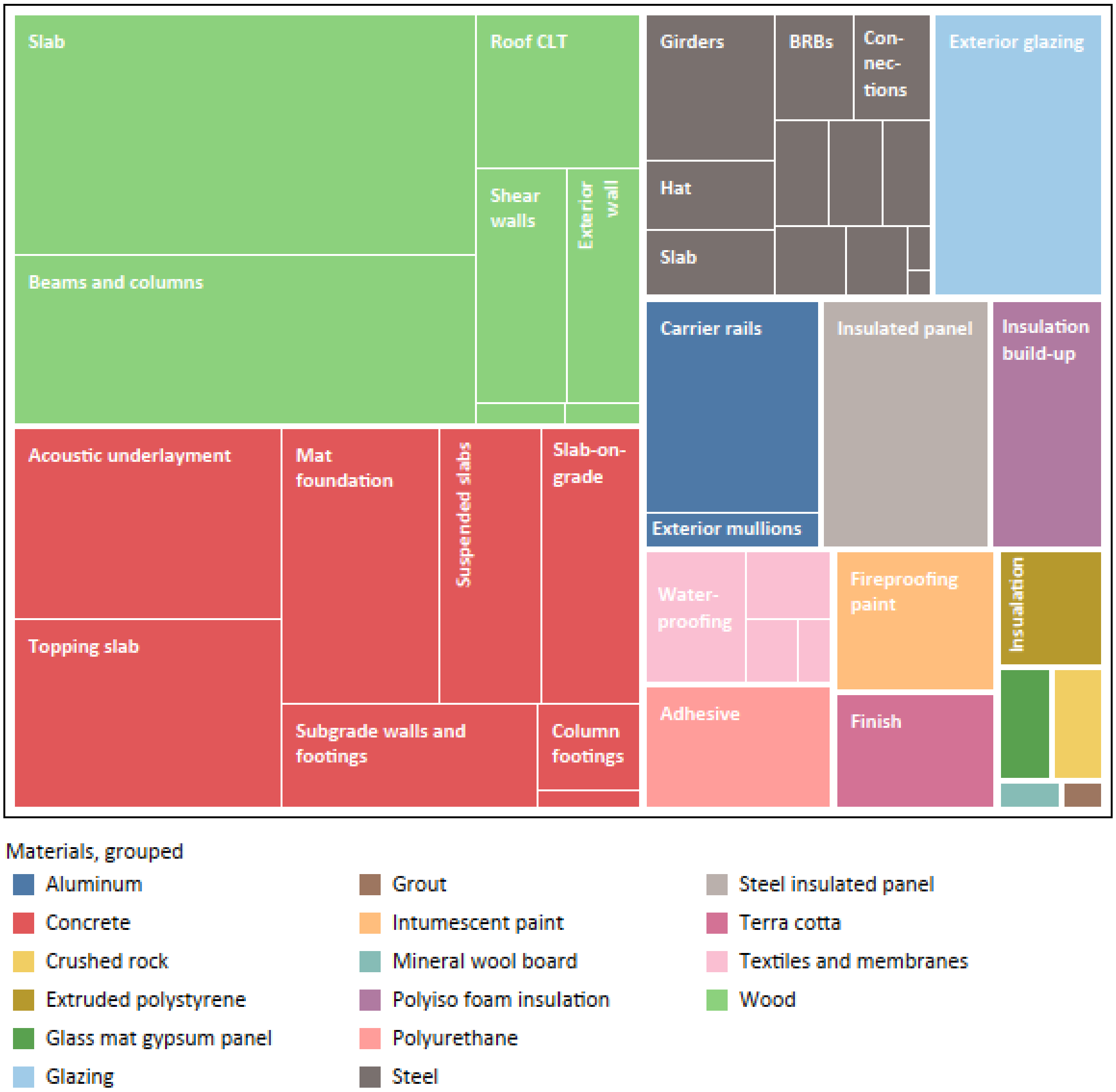


Figure 21. Treemap of GWP results (life cycle stage A) labeled by item and color-coded by the material groups.

Figure 22 presents GWP vs mass of the items in the building, color-coded by the material groups. The items in the lower-left corner are not labeled due to space constraints. However, the important items are the ones farther along the axes. This graph provides a sense of which items have high overall GWP on the project, which items have high overall mass, and which items are both, i.e. carbon intensity vs mass intensity.

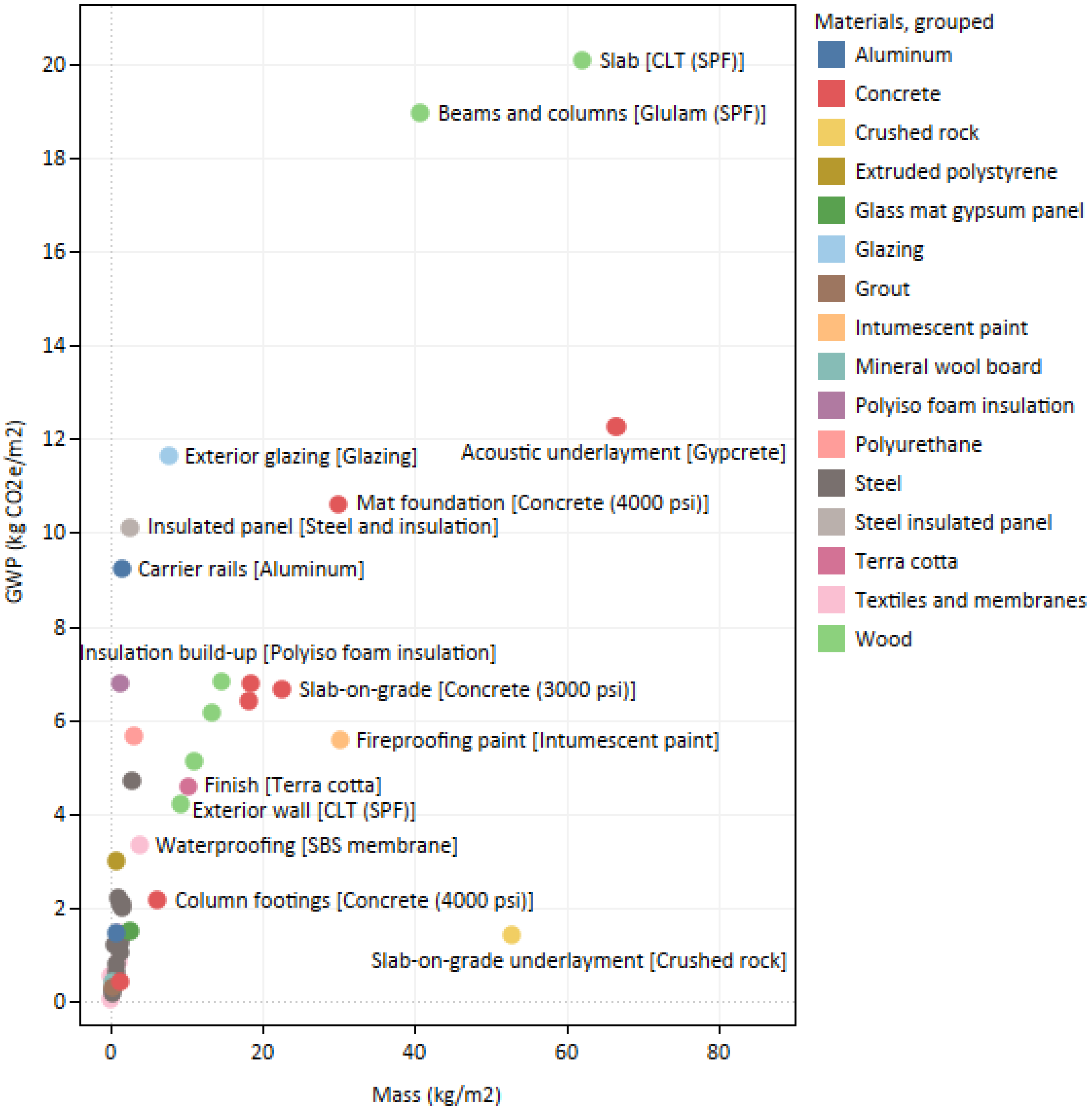


Figure 22. GWP (life cycle stage A) vs mass of items in building.

Items that have relatively high GWP but relatively low mass on the project are:

- Exterior glazing (glass)
- Insulated metal panel (steel and insulation)
- Carrier rails (aluminum)

- Insulation build-up in the roof (polyiso)

Items that have relatively low GWP but relatively high mass are:

- Slab-on-grade underlayment (aggregate, or crushed rock)

Items that have both high GWP and high mass in the building are:

- CLT slabs and glulam beams and columns
- Concrete items (especially the gypcrete topping slab and concrete mat foundation)

Carbon storage

This study treated biogenic carbon in accordance with the North America Product Category Rule (FPInnovations 2015) and the default TRACI impact method was used. Under the carbon neutrality assumption of wood products, TRACI does not account for CO_2 emitted through woody biomass consumption toward the final global warming impact but accounts for all other emissions other than CO_2.

The quantity of carbon stored in the building was calculated as follows. Since "carbon storage" could refer to the quantity of stored elemental carbon or stored carbon dioxide, both the elemental carbon and carbon dioxide versions are provided here.

Assumptions:

- From building data, the total volume of wood on project (CLT + glulam + cladding): 4,165 m3
- Density of SPF: 420 kg/m3 (SPF density was used because 99% of the wood volume on the project was SPF)
- % carbon of wood by weight: 50% (approx assumption)

Calculations:

Total weight of wood = (4,165 m3) * (420 kg/m3) = 1,749,451 kg

Total weight of stored elemental carbon:

= (1,749,451 kg wood) * (50% kg C / kg wood)

= 874,725 kg C = 874.7 metric tonnes C

= 55.8 kg C/m2

Total weight of stored carbon dioxide:

= (1,749,451 kg wood) * (50% kg C / kg wood) * (44 kg CO2 / 12 kg C)

= 3,207,326 kg CO2 = 3207 metric tonnes CO2

= 204.4 kg CO2/m2

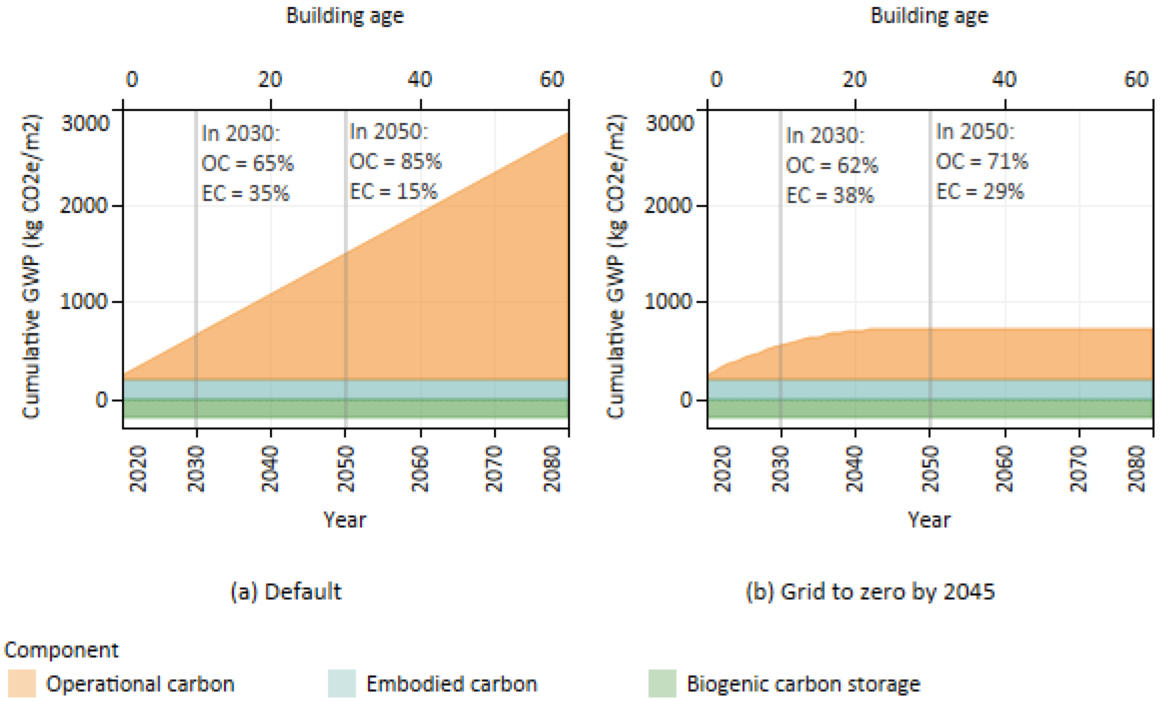
Given that the overall GWP of the building was calculated to be 207 kg CO2e/m2, this carbon storage result nearly offsets the embodied carbon impact of construction. Therefore, one could say that the biogenic carbon storage practically offsets the impacts of construction, at least in the near-term before the wood decomposes in a landfill at end-of-life. However, in order to rigorously incorporate the benefit of carbon storage into LCA results, a dynamic approach should be used, which takes into account the time when emission and sequestration occur.

Operational energy

Figure 23 presents a projection of operational energy alongside the embodied impact of construction as well as approximate stored CO_2. The assumed lifetime of the building was 60 years, which is typical in building LCAs. Two energy grid scenarios are shown:

(a) Default: Assumes that the emissions from the electrical grid stay constant
(b) Grid to zero by 2045: Assumes that emissions from the electrical grid steadily decline to zero by 2045 (i.e. a clean energy grid). This scenario is based on legislation passed in Washington State in April 2019 requiring 100% clean energy by 2045 (U.S. News 2019).

The projected cumulative GWP impacts of the two scenarios are shown in Figure 23. The vertical gray lines at the year 2030 and 2050 are labeled with the percentage of operational carbon (OC) and embodied carbon (EC) at that point in time.



(a) Default

(b) Grid to zero by 2045

Figure 23. Operational energy projection for (a) default scenario with constant electricity grid output, (b) scenario where the electrical grid declines to zero by year 2045. OC = operational carbon, EC = embodied carbon.

Discussion

This section presents a discussion of the results.

Hot spots and opportunities for improvement

This subsection discusses hot spots and opportunities for improvement separately for 1) the CLT production, and 2) the Catalyst Building.

CLT

The production capacity of Katerra is expected to increase in the near future. As the largest CLT manufacturing facility in the U.S., Katerra can produce 187,000 m3 of CLT at just 85% of its full production capacity. This larger capacity could make the Katerra facility more efficient compared to CLT facilities of smaller capacities, leading to lower environmental impacts. Further, the lumber used at the Katerra CLT facility is SPF, which is a lighter material compared to lumber produced using other common wood species combination in the Pacific Northwest, for instance, Douglas-fir or Western Hemlock. The lighter wood species helped reduce the impacts associated with transportation.

There are several recommendations that may help further increase the production efficiency while reducing environmental impacts:

1. Obtaining lumber from local sources can reduce the environmental impacts significantly. The average distance between Katerra's CLT facility and the sawmills is approximately 328 km in the current model. If Katerra can source the lumber within a 100-km radius, the total impact of lumber transportation alone may be reduced by as much as 70%. Further, improving the sourcing of lumber is more feasible than changing the input of the production process.
2. Currently, the lumber purchased by Katerra is round-edged. Round-edged lumber requires additional cutting to square the edges before CLT can be produced, leading to additional waste. If possible, Katerra could purchase square-edged lumber to help reduce waste and energy consumption resulting from lumber preparation.
3. Currently, to reduce the moisture content from 19% to 12%, the lumber is dried at Katerra's CLT facility using a natural gas kiln (this drying step occurs under "Onsite CLT Manufacturing" > "Lumber Infeed"). An alternative method for reducing the environmental impact of drying

would be to dry the lumber at the sawmill using hog fuel, which is a waste product of lumber production.

Catalyst Building

This section identifies the highest-impact components and materials of the building and offers strategies for impact reduction.

In the structure of the building, the highest-impact items are ranked as follows (in descending GWP):

1. **Slabs:** Slabs are typically the most massive part of a structural system, so this ranking is expected. The GWP impact contribution of the structural slabs is approximately 70% CLT, 25% GLT, and 7% steel connections. For impact reduction opportunities for CLT, see the earlier hot-spot analysis for the CLT LCA. With regards to material reduction, the research team assumes that the design team designed the slabs for optimal structural and material efficiency, but offers the following options as general strategies that can help optimize structural mass and thus minimize the environmental impacts of the structural slabs:
    a. Add intermediate beams in the structural bays
    b. Avoid charring design as a method of fireproofing (use alternative methods of fireproofing)
    c. Reduce column spacing
2. **Beams and columns**: The glulam beams and columns have the next-highest impact. Most of the impacts are likely due to the beams. The mass of the beams may be reduced by exploring the same strategies listed under '1. Slabs.'
3. **Acoustic underlayment, topping slab,** and **mat foundation** all have approximately the same GWP impact. The design of these building components probably cannot be optimized further. However, lower-impact concrete and gypcrete may be achieved by focusing on cement. The impact of cement can be lowered by 1) reducing the amount of cement in the mix, 2) substituting with lower-impact cement alternatives, such as fly ash or blast furnace slag cement, or 3) using concrete that contains carbon dioxide injections (see www.carboncure.com). Carbon-storing aggregate is also an option (see www.blueplanet-ltd.com).

The next three highest-impact items can be found in the enclosure. Without seeing the actual building plans and understanding the design considerations, the research team can only generally recommend minimizing the use of these enclosure items. These items are (in descending GWP):

4. **Exterior glazing:** Glass for glazing is energy-intensive to produce, and thus tends to be relatively high in embodied carbon.
5. **Insulated metal panel:** Insulated metal panels are high in embodied carbon because they have metal, usually steel, which is traditionally high in embodied carbon, especially if it is produced from a blast oxygen furnace (BOF) instead of an electric arc furnace (EAF). In the case of the Kingspan product used on this project, "in the sourcing and extraction stage, the largest contributors to the impacts in terms of raw materials are steel (46%) and foam (30.5%)" (Kingspan 2019), so the foam is also relatively high in environmental impacts.
6. **Aluminum carrier rails:** Aluminum is also environmentally-intensive to produce. In some cases, its GWP impact can be six times higher than that of steel, kg per kg.

Comparison to other buildings

This section presents a simple comparison of the Catalyst Building GWP results with other relevant studies. It is important to note that the intent of this section is not to make comparative assertions of environmental performance, since there are limitations in this study and the other studies that preclude their comparability. Instead, this section merely demonstrates that the embodied carbon of the Catalyst Building are on the same order of magnitude as other similar buildings.

Figure 24 compares the Catalyst Building results with a number of other wood case study LCAs:

- Brock Commons Tallwood House at University of British Columbia, Canada (Bowick, n.d.)
- Carbon 12 in Portland, Oregon (Kaiser 2019), (ThinkWood 2019)
- T3 Minneapolis in Minnesota (Johnson 2018). The two X's shown are for 1) a cradle-to-gate assessment (approximately 130 kg CO2e/m2) and 2) a cradle-to-grave assessment (approximately 195 kg CO2e/m2).
- An 8-story apartment building in Sweden (Gustavsson et al. 2010)
- A 5-story office building in Canada (Robertson et al. 2012)
- Three versions of a reference building based on three LCA tools in Sweden (Sinha et al. 2016)

- Best-case and worst-case scenario from a study based on a hotel structure in Norway (Skullestad et al. 2016)
- Three 4-story residential buildings in Australia (Lu et al. 2017)
- Two hypothetical 8-story office buildings in the Pacific Northwest (Pierobon et al. 2019)
- Multiple buildings from the Embodied Carbon Benchmark study, limited to North American buildings, mid-rise office type (7-14 stories, since there was only one low-rise office building with these other criteria), structure only (Simonen et al. 2017). Note that none of these buildings had a wood structural system.

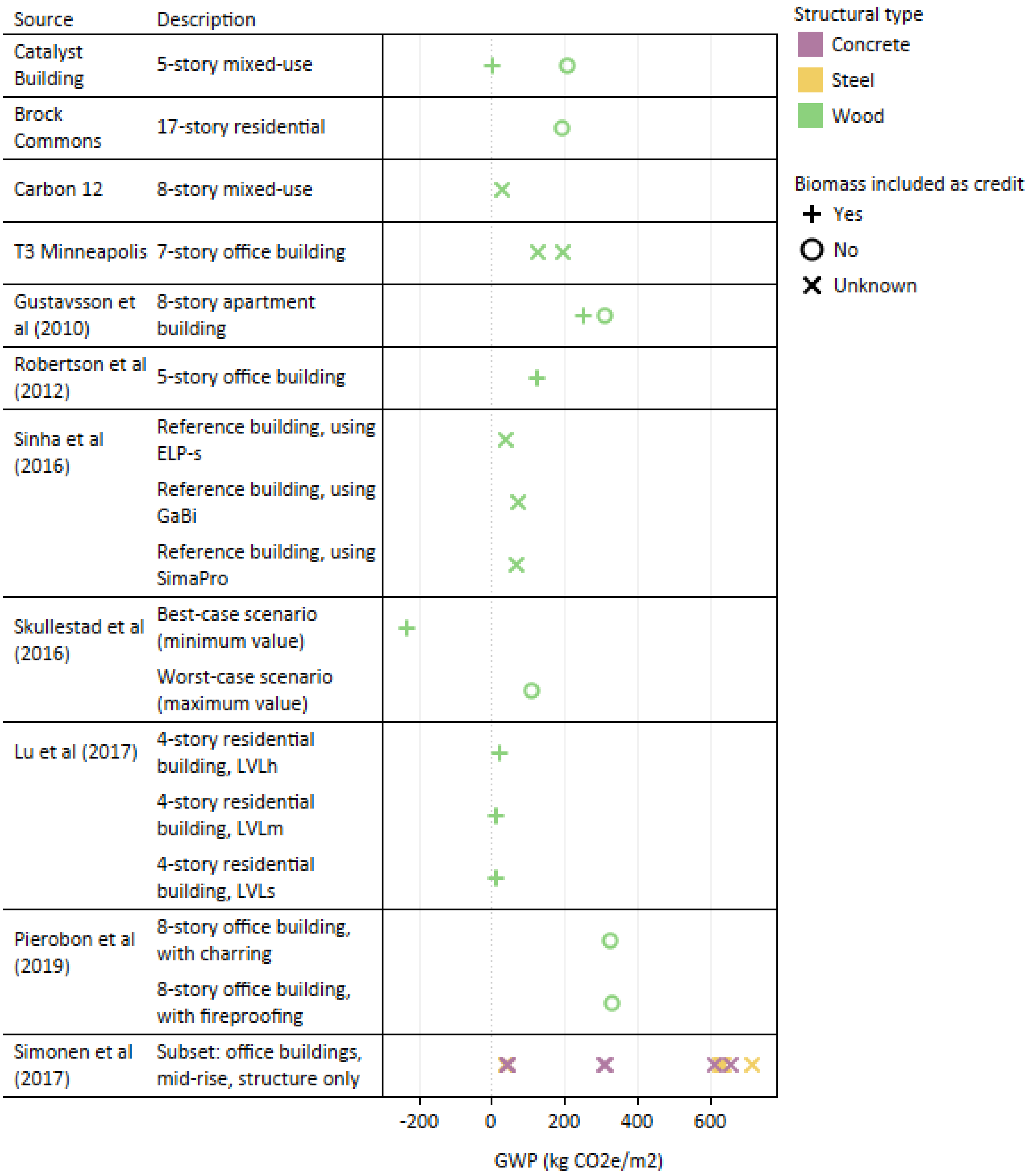


Figure 24. Comparison of the Catalyst Building with other studies.

Figure 25 presents a subset of the buildings presented in the previous figure, limited to the studies that had the most similar LCA assumptions to this study (wood structure, life cycle stage A, excluding biogenic carbon credit). This figure shows that the Catalyst Building results are on the same order of magnitude as other similar studies.

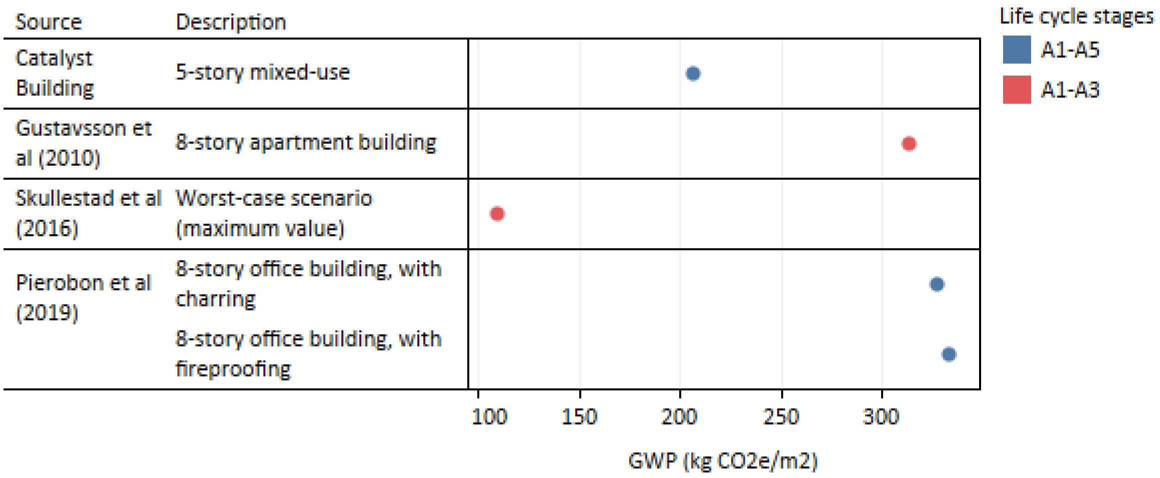


Figure 25. Comparison of the Catalyst building with other wood case studies, limited to studies with similar LCA assumptions.

Conclusion

A life cycle assessment was performed on Katerra's new CLT supply chain and manufacturing process as well as one of Katerra's buildings under construction, the Catalyst Building, in Spokane, Washington. Based on the results of the LCA, the research team found the following opportunities for environmental impact reduction:

- For the CLT manufacturing:
    - Obtain lumber from more local sources.
    - Purchase square-edged lumber instead of rounded-edge lumber, if possible.
    - Consider alternative drying methods for lumber drying, such as drying at sawmill with hogfuel instead of onsite at the CLT manufacturing facility with a natural gas kiln.
- For the Catalyst Building:
    - Reduce the amount of materials in the floor system (slabs and beams) by reducing the impacts of CLT (above) and/or exploring the alternative geometric configuration of the bays.
    - Lower the impact of gypcrete and concrete by 1) reducing the amount of cement in the mix, 2) substituting Portland cement with alternative cementitious materials, and 3) consider carbon dioxide injection or carbon-storing aggregate.
    - Reduce the quantity of high-impact construction materials generally, which include: concrete, glazing, and metal items in the cladding such as insulated metal panels and aluminum carrier rails.

After conducting this short study, the research team sees many opportunities to refine the LCAs of the CLT model and the Catalyst Building. Proposed future work are as follows:

- **Collect more data from the factory after a year of operations.** The factory had just begun production when this study was performed, so collecting additional information after factory operations have been established would help refine the model.
- **Perform more sophisticated biogenic carbon calculations.** The carbon storage calculations presented in this report are simple, but a more sophisticated analysis including more aspects of the supply chain could be done.

- **Incorporate Avista electricity data into energy calculations**. One reviewer inquired about using actual mix data from the local electricity provider (Avista). The research team did not have time to request data from Avista within the time frame of the project deadline, but would be interested in developing the results based on the specialized grid. It should be noted that using generic LCI electricity grid data, such as eGRID, is common practice and widely-accepted for LCAs.
- **Limit building LCA to A1-A3 only**. This study considered all of life cycle stage A, but limiting the life cycle scope to A1-A3 would increase the internal comparability of the LCA data.
- **Refine concrete material quantities with concrete mix designs**. As mentioned in "Methodology" > "Catalyst Building" > "Material quantities and LCA data" > "Concrete," two mix designs were not used in this analysis. The material quantities were not provided according to the mix designs, so some assumptions had to be made. The research team would be interested in refining the concrete LCA results by working with Katerra to revise the concrete material quantities specific to each mix design.

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