LIFE CYCLE ENERGY AND ENVIRONMENTAL IMPACTS OF CROSS LAMINATED TIMBER MADE WITH COASTAL DOUGLAS-FIR

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ABSTRACT

In this study, a cradle-to-gate life-cycle assessment (LCA) of Oregon-made cross-laminated timber (CLT) was conducted as per the ISO guidelines. Primary data pertaining to CLT manufacturing was collected from a production facility in Oregon and modeled with existing LCA data of Pacific Northwest softwood lumber production and harvesting operations. Primary energy is reported and encompasses all processes within the system boundary. Carbon emissions are reported and include fossil-based emissions from transportation and all production processes and carbon storage in CLT. LCA results are presented for five impact categories, primary energy consumption, and net carbon impact of CLT. Results show the environmental advantage of CLT due to storing of large amounts of biogenic carbon in a building structure for a lifetime. The amount of carbon stored in CLT offsets the emissions released from all production processes; this indicates that CLT is a net negative carbon emitter, as more carbon is stored in the product than is emitted to produce the product. This study shows the importance of using the LCA methodology for showing the net amount and type of energy used for production and the potential climatic impacts of using wood products. This LCA study makes no comparative assertions.

KEYWORDS

life-cycle assessment, CLT, energy, carbon impacts, cradle-to-gate

INTRODUCTION

Sustainability of resources and environmental impacts for extraction and production are becoming important considerations when deciding on a suitable structural material for a building or infrastructure project (Sinha et al. 2013). Since the environmental impacts and benefits of wood use have been well documented over the base decade (Bergman and Alanya-Rosebaum 2017a; Bergman and Alanya-Rosebaum 2017b; Bowers et al. 2017; Milota and Puettmann 2017; Milaj et al. 2017; Oneil and Puettmann, 2017, Salazar and Meil 2009), it has become

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a material of choice for building structures with an enhanced sustainability goal. Wood-based materials have been shown to outperform steel and concrete assemblies over several impact categories, including energy and solid waste. Perez-Garcia et al. (2005) reported that wood floor assemblies used 67% less energy and 157% less carbon emissions, and 312% less water consumption from cradle to grave than an equivalent steel assembly.

Building construction and use contributes almost 40% of United States (U.S. carbon dioxide (CO_2) emissions and about 41% of total U.S. energy consumption (DOE 2010). Building operations is the main contributor, along with building material and construction practices (Dixit et al. 2010). Although wood is the primary building material in single-family, residential construction, however, there is limited application in mid-rise and commercial buildings. With the introduction of mass timber products, specifically cross laminated timber (CLT) the dynamics of the building industry is changing.

Cross-laminated timber is leading the mass timber movement, which is enabling designers, engineers, and other stakeholders to build taller wood buildings. It is a mass timber panel made by laminating dimension lumber orthogonally in alternating layers. CLT has many environmental advantages as a natural carbon store and that its use generates virtually no waste at a building site, as panels are generally prefabricated before delivery. CLT panels are lightweight, yet very strong, with good fire, seismic, and thermal performance. The recently completed Brock Commons building in Vancouver, British Columbia, is only one of many testimonies to the gaining momentum of the mass timber movement. The perceived benefit of using CLT as compared to other building materials because of its superior environmental performance can be validated by using the robust life-cycle assessment (LCA) methodology. LCA is the best tool for determining energy use and the potential climatic impacts of buildings with CLT.

LCAs of wood buildings have shown that these buildings have a negative carbon footprint. A negative carbon footprint occurs when the final use product stores more carbon than is emitted through the production and use processes. For a standard wood-frame structure, Gustavasson et al. (2010) reported a net emissions of –62 kg CO_2 equivalent per square meter (eq./m^2) for the entire life cycle of a building (50 years). When the life cycle is pushed out to 100 years, the net building carbon emissions is 251 kg CO_2 eq/m^2, with the increase coming from operational (heating and cooling) impacts. Wallhagen et al. (2011) reported that substituting reinforced concrete slabs with laminated wood reduced the impact by 25%. When carbon sequestration is accounted for, a CLT building system has the potential to have greater negative impacts than a standard wood-framed building and a much higher environmental advantage over non-renewable materials, especially in the Pacific Northwest (PNW) where designing for seismic standards can be significant in material use. In cradle-to-gate assessments of Canadian CLT (Structurlam 2013), net carbon impacts have been reported at –678 kg CO_2 eq/m^3 (estimated –99 kg CO_2 eq./m^2), which can position CLT with a high environmental advantage over non-wood materials.

In Canada, the LCA conducted by Robertson et al. (2012) comparing a CLT building to a traditional reinforced-concrete building showed that wood was advantageous in 11 out of 12 impact categories, with a global warming potential (GWP, kg CO_2 eq.) reduction of 71%. Since primary data on the manufacturing of CLT and impacts associated with them was not captured at the time of the particular study, Robertson et al. (2012) assumed that the production of glue-laminated beams was applicable to CLT production on a volume basis. This is a major drawback of the study, and it emphasizes the need to obtain primary data on CLT production and use. In the absence of primary data on CLT, any comparison using LCA that is based on certain assumptions will have limited scope and may be subject to criticism. Consequently, there is a pressing need to collect primary data on CLT manufactured in the U.S. and to conduct an LCA of the product. At the time of this writing, there were only two certified structural CLT manufacturer in the U.S.—one in Oregon and the other in Montana. The Oregon manufacturer is the first plant established in the U.S. that produces certified CLT panels and is amongst the largest; an LCA of their product line has been conducted and the results are presented herein. When this LCA was conducted, the certified panels produced from the Oregon CLT manufacturing facility were solely composed of coastal Douglas-fir laminating stock (lamstock).

USE OF CLT IN BUILDING STRUCTURES

CLT can be utilized within a building as a gravity system for above-grade applications, as well as for lateral systems like shear walls (Figure 1). Predominantly, CLT is used along with other traditional materials, in a variety of building construction applications and thus, resulting in a hybrid construction. The Brock Commons building in Vancouver, Canada, is a good example of a hybrid system, with a concrete lateral force resisting core and wooden gravity system. Using a wide range of design parameters, a "hybrid CLT building" study estimated the potential use of CLT in various applications for mid-to-high rise buildings (Ganguly et al. 2017). The model provided estimates for the bill of materials for a gravity system of a hybrid CLT building. In a hybrid CLT building, concrete and rebar can be replaced with CLT in slab applications (horizontal diaphragms) using a direct substitution approach and with glulam beams substituted for the columns. In most cases, CLT would be used in conjunction with other traditional materials. For example, CLT and concrete composite floors were installed in the John W. Olver Design Building at the University of Massachusetts, Amherst (UMass Amherst 2018). The final volume of CLT used in a building would depend on end-use specific material substitution and the regional building code restrictions (Karacabeyli et al. 2013; Ganguly et al. 2017).

ENVIRONMENTAL STANDARDS

There are standards in place for conducting LCAs. The International Organization for Standardization published requirements and guidelines for conducting LCAs (ISO 2006a). Lifecycle assessments conducted solely under the ISO standard might not necessarily report on

FIGURE 1. CLT used in various application. CLT as a floor assembly with concrete and CLT and glulam wall assemblies, John W. Olver Design Building at the University of Massachusetts, Amherst. Photo credit Alex Schreyer (Left). A CLT wall component being installed, Peavy Hall, Oregon State University (Right). Photo credit Arijit Sinha.

the same functional unit or even report the same impacts. Product Category Rules (PCR) make it easy to consistently evaluate environment impacts of products and facilitate comparisons. A PCR is a set of rules, requirements, and guidelines following international established protocols to develop environmental product declarations (EPD) (ISO 2006a 2006b). The users of a PCR can be manufacturers of wood products, architects, builders, and other interested parties. A PCR presents a structure that is intended to ensure a harmonious approach to derive, verify, and present EPDs for solid wood building products in North America.

An EPD is a document that provides, in a user-friendly format, the environmental impacts, energy usage, and other information that results from a science-based LCA of a product. EPD development is based on a set of international standards (ISO 2006a, 2006b) outlined in the PCR that defines the processes to be used when evaluating some or all of the product's life-cycle stages. An EPD provides the basis for an evaluation of the environmental performance of products but does not "judge" whether the product or service meets any environmental quality standard. Users of EPDs are able to make their own judgments based on the information presented. Most importantly, perhaps, an EPD is a disclosure by a company or industry that makes public the standardized environmental impacts of its products. While an EPD would not include comparisons between products or make reference to any environmental benchmark or baseline, when properly structured and verified against the same PCR, an EPD for one product can be used for comparison against the EPD for another. The key is that for realistic comparisons the functional unit must be the same.

METHODS

Life Cycle Assessment

Life-cycle assessment is an internationally accepted method to analyze complex impacts and outputs of a product or process and the corresponding effects they might have on the environment. LCA is an objective process to evaluate a product's life cycle by identifying and quantifying energy and materials used and wastes released to the environment; to assess the impact of those energy and materials uses and releases on the environment; and to evaluate and implement opportunities to effect environmental improvements. More details about the LCA methodologies and standard can be found in Milota and Puettmann (2017) and Oneil and Puettmann (2017), where the reader is directed for more background. This study can be categorized as a cradle-to-gate LCA, as it includes forestry operations using sound-secondary analysis though the manufacturing of CLT ready to be shipped at the mill gate.

Scope

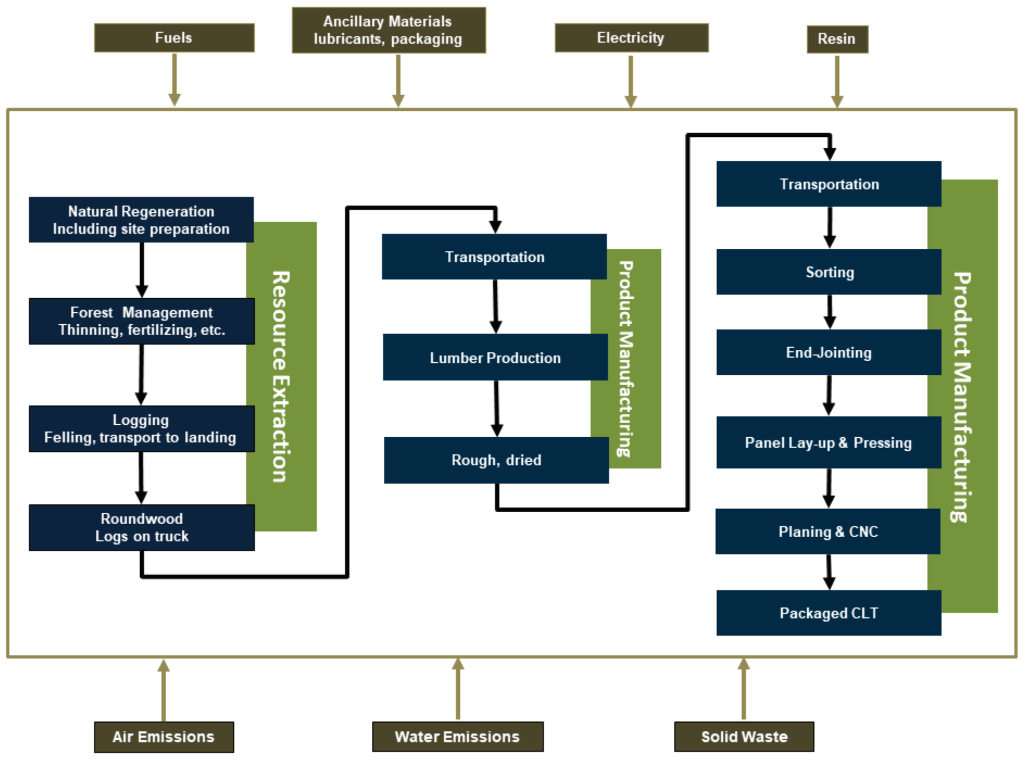
The scope of this study was to develop a cradle-to-gate LCA of CLT using upstream processes for wood production common to practices and technology specific to the Pacific Northwest U.S. The LCA of CLT includes the impact in terms of material flow, energy type and use, emissions to air and water, solid waste production, and water impacts for the CLT process on a per unit volume basis of 1.0 cubic meter (m^3). Data for the LCA are based on gate-to-gate inputs and outputs obtained directly from the manufacturer; recently published data for gate-to-gate softwood lumber production (Milota and Puettmann 2017) and cradle-to-gate forest resources LCI's (Oneil and Puettmann 2017) were used for the upstream process inputs for CLT production. This is a commonly accepted process in mainstream LCA where a mix of secondary and primary data is used for analysis.

All input and output data were allocated to the declared unit of product based on the mass of products and co-products in accordance with standards for conducting LCA's (ISO 2006a), which makes this a cradle to CLT manufacturing gate LCA with no service life assigned to the CLT. The declared unit for CLT is 1.0 m^3 (or 35.3 ft^3). A declared unit is used in instances where the function and the reference scenario for the whole life cycle of a wood building product cannot be stated. All input and output data were allocated to the declared unit of product, based on the mass or economic basis of products and co-products in accordance with ISO protocol (ISO 2006a) and the PCR (FPInnovations 2015) for future EPD development. This analysis does not take the declared unit to the stage of being an installed building, so no service life is included in the results.

System Boundaries

The system boundary begins with regeneration in the forest and ends with the CLT product at the gate of the CLT production facility (Figure 2). The system boundary includes forest operations, which may include site preparation and planting seedlings, fertilization and thinning, pesticide and or herbicide use, and final harvest with the transportation of logs to the lumber production facility, transportation of lumber to CLT manufacturing site, and onsite production of CLT. The CLT production complex was modeled as a single unit process. The study recognized five steps necessary to make CLT. Excluded from the system boundaries are fixed capital equipment and facilities, transportation of employees, land use, delivery of CLT to construction site, construction, maintenance, use, and final disposal.

FIGURE 2. System boundary for cradle-to-gate CLT manufacturing.



Allocation Method

Cross laminated timber is the main product in the manufacturing process. We used two allocation approaches: 1. mass allocation and 2. economic allocation. A mass allocation is the most common allocation approach and measured with high accuracy. Mass allocation also allowed for the comparison with equivalent building materials in design assemblies. On a mass basis, 83% of the input wood material is applied to the CLT product. We also used an economic allocation to stay within conformance of the PCR in case an EPD was later to be developed for Oregon CLT. For the economic allocation we assumed that of the CLT product had a value greater than 10 times the value of the coproducts (shavings, waste, off specs and end cuts) therefore, no allocation was assigned to the coproducts allowing 100% of the impacts allocated to CLT.

Impact Assessment

The life-cycle impact assessment (LCIA) phase establishes links between the life-cycle inventory results and potential environmental impacts. The LCIA calculates impact indicators, such as global warming potential and smog. These impact indicators provide general, but quantifiable, indications of potential environmental impacts. The target impact indicator, the impact category, and means of characterizing the impacts are summarized in Table 1. Environmental impacts are determined using the Tool for Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI) method (Bare 2011). These five impact categories reported are consistent with the requirements of the wood products PCR (FPInnovations 2015), which are requirements for a product environmental declaration.

Each impact indicator is a measure of an aspect of a potential impact. This LCIA does not make value judgments about the impact indicators, meaning comparison indicator values are not valid. Additionally, each impact indicator value is stated in units that are not comparable to others. For the same reasons, indicators should not be combined or added.

The cumulative energy demand (CED) impact method was used for summarizing primary energy (coal, oil, natural gas, nuclear, biomass, hydro, and other renewables). The primary fuels were further categorized into non-renewable fossil, non-renewable nuclear, renewable woody biomass, and other renewables (hydroelectric, wind, solar, geothermal). The CED impact method was adjusted to include the mill residues used for heat energy in the western softwood lumber model. Table 1 summarizes the source and scope of each impact category reported.

Consideration of Biogenic Carbon

The forest products industry is consistently challenged regarding its environmental sustainability. The greatest challenges with respect to practices center on the extraction of forest resources, with questions about carbon stores and flows in the forest environment. Carbon dioxide is considered the primary contributor to the rise in global temperatures and is released from the combustion of fossil and biomass fuels.

The appropriate methodology for assessing the impacts of CO_2 releases and other greenhouse gases is GWP, which compares the amount of heat trapped by a certain mass of the gas in question to the amount heat trapped by a similar mass of CO_2. GWP is an indicator that reflects the relative effect of a greenhouse gas in terms of climate change, considering a fixed time-period, commonly 20, 100, or 500 years. For example, the 20-year GWP of methane is 56, which means if the same weights of methane and CO_2 were introduced into the atmosphere, methane would trap 56 times more heat than the CO_2 over the next 20 years.

TABLE 1. Impact category sources and scope.

Impact category	Unit	Method	Level of site specificity
Global warming	kg CO_2 eq	TRACI 2.1 v1.01	Global
Smog	kg SO_2 eq	TRACI 2.1 v1.01	North America
Acidification	kg N eq	TRACI 2.1 v1.01	North America
Ozone depletion	kg CFC-11 eq	TRACI 2.1 v1.01	North America
Eutrophication	kg O_3 eq	TRACI 2.1 v1.01	North America
Total energy	MJ	CED	Global
Non-renewable fossil	MJ	CED	Global
Non-renewable nuclear	MJ	CED	Global
Renewable woody biomass	MJ	CED—modified	Global
*Other renewables**	MJ	CED	Global

* solar, wind, hydro, geothermal

Standards such as ASTM D7612 (2015), which are used in North America to define legal, responsible, and/or certified sources of wood materials, are in place to provide assurances regarding forest regeneration and sustainable harvest rates that serve as proxies to ensure stable carbon balances in the forest sector. They are outside the accounting framework for this LCA.

Forest Resources Inputs

The wood extraction stage provides estimates of the yield and emissions associated with the management of representative timber-producing acres for the area west of the Cascade Mountains in Washington and Oregon, in what is commonly called the PNW Douglas-fir region. Data for resource extraction was based on the cradle-to-gate LCA by Oneil and Puettmann (2017) and adjusted where necessary to represent only Douglas-fir. This region is dominated by temperate coniferous rainforests comprised mainly of Douglas-fir (*Pseudotsuga menziesii*) and western hemlock (*Tsuga heterophylla*), with other species such as spruce (*Picea* spp.), true firs (*Abies* ssp.) and western redcedar (*Thuja plicata*) making up a smaller component of the harvested softwood volume. Only the harvest of Douglas-fir timber was considered in the LCA on CLT. Harvests were predominately from large private and industrial landowners (Oneil and Puettmann 2017). The gate-to-gate process for PNW forest operations considers landscape-level impacts. The potential impacts to soil carbon and biodiversity are outside the scope of this analysis. Under a mass allocation approach, roundwood harvested and delivered from the roadside was 1.09 m^3/m^3 of CLT (1.86 m^3/m^3 using an economic allocation).

Lumber Inputs

Douglas-fir kiln-dried rough saw lumber is the wood input for CLT. Lumber is produced in Oregon following processes outlined by Milota and Puettmann (2017). Rough dry lumber is delivered by truck from the supplier to the CLT facility. The weighted average amount of wood only in a CLT panel is 537 kg/m^3, requiring a total of 649 kg of oven-dry rough lumber or 1.21 m^3 for both product and coproducts produced. For mass allocation, only 83% of the 649 kg of lumber input is assigned to CLT. However, in the case of an economic allocation 100% of the lumber input is assigned to CLT.

CLT Production

Cross-laminated timber is a multi-layered structural wood product constructed of large panels made from solid wood and glued together in alternating directions of their fibers. CLT panels consist of an odd number of layers (usually three to seven) and may be sanded or prefinished before shipping. While at the mill, CLT panels are cut to size, including door and window openings, with state-of-the art computer numerical controlled (CNC) routers capable of making complex cuts with high precision.

The Oregon CLT facility used for this study is located in southern Oregon along the Interstate 5 corridor. Oregon CLT is manufactured with Douglas-fir lumber in accordance with the V1 or custom grade of ANSI/APA PRG 320 (2018). CLT panels can be used in floor, roof, and wall applications and are manufactured with nominal widths of 0.305–3.05 m (1–10 ft), thicknesses of 10.48–24.45 cm (4-1/8 to 9-5/8 inches), and lengths of up to 12 m (42 ft). The CLT produced in this facility is certified by the American Panel Association (APA).

Cross-laminated timber is produced from 2×4-12, #2 and #3 or MSR graded lumber dried to 12% (+/– 3%) moisture content. The production begins with the lumber entering a sorting line where it is planed to 1-3/8 inch. The lumber is then sorted by grade and moisture content. The lumber is then vertically finger jointed using a melamine-based resin and cured using a radio frequency dryer. After a final quality check, the finger-jointed lumber is moved to assembly trays. Assembly of a 3-layer CLT panel would include higher-quality lumber pieces placed as a first layer, then a melamine glue is applied, then a lower-grade lumber is layered perpendicular to the first, followed by another glue application and another layer of higher-grade lumber. CLT panels can be constructed in this manner to produce panels of 3, 5, 7, or in some cases 9 layers. Once the panel is assembled, it is pressed using pneumatic cylinders to 110 psi for approximately 30 minutes. Panels exit the press and are lifted by forklift to a CNC machine. The final step before shipping is that the CLT panels are sanded and wrapped for protection during shipment.

The CLT production LCI input data was based on 2016 production from the Oregon manufacturer. Data is based on a production of 3,398 m^3 (3.05 × 7.32-m panels) of CLT per year. At the time of data collection, the Oregon facility was still in a preliminary production phase, so production and data based on the capacity of the facility was used for 2016. A weighed average of three panel sizes represents the 3,398 m^3/year and is shown in Table 2.

Cross-laminated timber is the main product in the manufacturing process, comprising 98.6% wood and 1.4% resin by mass (Table 3). There is no waste wood product sent to a landfill or burned onsite for energy. These findings are consistent with recent wood product LCI industry-wide surveys (Milota 2015). All wood waste generated by finger jointing, planning, and the CNC machine are considered coproducts and leave the CLT system boundary with some economic value to them. Based on the lumber input into the CLT facility, 83% ends up in the CLT product, and 17% as coproducts. These coproducts are used for energy off site or feedstock for particleboard manufacturing.

TABLE 2. Panel sizes and allocation for a weighted-average CLT panel from Oregon manufacturer.

CLT Panel	Allocation of panels	ft^3/panel	ft^3/yr.	m^3/yr.	# Panels/yr.	Board ft/yr.
3-Layer	30%	82.5	36,000	1,019	436	741,701
5-Layer	60%	137.5	72,000	2,0391	524	1,483,402
7-Layer	10%	192.5	12,000	340	62	247,234
TOTAL	100%		120,000	3,398	1,022	2,472,336

ft^3/bf = 0.049 (actual)

Transportation Inputs

The transportation of logs from the forest roadside after harvest is the first transportation process for CLT manufacturing (Table 4). Logs for the Oregon CLT manufacturer are delivered from western Oregon to a softwood lumber production facility in Mill City, Oregon. As previously noted, rough planed lumber is the feedstock input for CLT. It is transported by truck from the sawmill facility to the CLT facility in southern Oregon, 169 miles away. The resin used in CLT is transported both by road and by barge. The wrapping material used for the CLT comes from the state of Washington by road.

TABLE 3. Mass balance of CLT and coproducts produced at the Oregon CLT facility.

Primary product	Unit	Amount/m^3	Mass allocation
Inputs			
Lumber inputs	odkg	648.81	100%
Resin portion	kg	7.45	
Outputs			
CLT	m^3	1	
CLT	odkg	544.68	82.8%
Wood portion	odkg	537.23	
Planar shavings	odkg	22.43	3.4%
Finger joint waste	odkg	6.05	0.9%
Hundegger waste	odkg	7.12	1.1%
CLT off spec and end cuts	odkg	75.98	11.7%

odkg = oven dry mass in kilograms

TABLE 4. Inputs for CLT production used to develop the life-cycle inventory.

Inputs	Unit	Amount	Mode of Transport
Logs to sawmill	mile (km)	67 (108)	Road
Lumber to CLT	mile (km)	169 (272)	Road
Resin	mile (km)	8,937 (14,373)	Barge
Resin	mile (km)	227 (365)	Road
Hardener	mile (km)	486 (782)	Road
Wrapping material—Packaging CLT	mile (km)	200 (322)	Road
Lumber	m^3	1.21	
Lumber	odkg	648.81	
Lumber delivery by truck	tkm	176.46	
MF resin	kg	7.45	
MF resin transport—ship	tkm	107.10	
MF resin transport—Truck	tkm	2.72	
Electricity	kWh	98.90	
Natural gas	m^3	4.18	
Diesel	L	0.05	

tkm = tonne-kilometer

Resin Inputs
Oregon CLT is certified to use a non-urea melamine formaldehyde resin, not the melamine-urea-formaldehyde resins more commonly used in structural laminated timber products in North America (Table 4). The resin is used for both finger jointing and face bonding the lumber in CLT production. The resin manufacturer for the Oregon CLT facility was AkzoNobel, which produces a low-emission melamine 2-part clear resin. The resin is LEED Gold certified and approved for interior and exterior use.

Energy Inputs
Energy and fuel requirements for the CLT production came from electricity, natural gas, and diesel at the CLT facility (Table 4). Electricity was modeled using the Northwest Power Pool Grid which includes coal, biomass, petroleum, geothermal, natural gas, nuclear, hydroelectric, wind, and other energy sources (NWPP 2010). The source of fuel used to generate electricity helps determine the type and amount of impact in the overall LCA. Non-renewable fossil represents nearly 55% of the fuel source in the NWPP grid, whereas hydro, wind, solar, and geothermal comprise about 41% of the electricity fuel sourcing. Oregon CLT production is new, and several updates have been made to the manufacturing of CLT since data was collected, e.g., installation of a CNC machine. The same facility produces cold-cure glulam, so it was

necessary to make assumptions about electricity, natural gas, and other fuels allocated to CLT. The manufacturing facility allocated 30% of the total on-site electricity use to CLT production.

RESULTS AND DISCUSSION

Results are presented for three life cycle stages:

1. Cradle-to-gate for forestry operations (forest operations, harvesting),
2. Gate-to-gate for softwood lumber production (transport of logs, lumber sawing, drying, and packaging), and
3. Gate-to-gate for CLT production using primary data.

Cradle-to-Gate LCIA Results

Environmental performance results for GWP, acidification, eutrophication, ozone depletion and smog, calculated using the TRACI impact method are reported in Table 5. The cumulative energy demand (CED) impact method results are also reported in Table 5 as total energy and energy generated from non-renewables, renewables, wind, hydro, solar, and nuclear fuels.

Both mass allocation and economic allocation results are reported in Table 5. Transportation is burdened to the receiving process, for example, log transport from the forest road is part of the gate-to-gate of softwood lumber production. Resin production transport impacts are part of the gate-to-gate CLT production. For our results, both lumber production and CLT production would have a mass or economic allocation approach applied to them. For lumber production, actual pricing for the lumber and coproducts was used, based on Milota (2015). For the economic allocation of CLT, the value of the CLT product was greater than 10 times the difference in economic value across coproducts; therefore, the environmental burden of CLT manufacturing is entirely allocated to CLT.

Recent studies have shown similar results in mass and economic approaches and highlight the pros and cons of each of these allocation approaches (Taylor et al. 2017). In various wood panel LCAs, an economic allocation of products and coproducts resulted in higher environmental impact for the main product. For Oregon CLT, the difference in impacts was a 30% increase in GWP from a mass allocation to an economic allocation, and 24% more energy when an economic allocation was assigned (Table 5). Economic allocation likely will not be required in the next round of PCR development. Consequently, our discussion of results is predominantly based on mass allocation. The economic allocation is presented along with mass allocation in order to highlight the differences and provide relevant and necessary information to the readers.

Aside from the differences between the two approaches, the production of 1 m^3 of Oregon CLT released 206 and 159 kg CO_2 eq. for economic and mass allocation, respectively. CLT production represented 57%–61% of the GWP impact, while lumber production and forestry operations accounted for 28%–27% and 16%–12%, respectively. A similar impact allocation was found in cradle-to-gate CLT production from Canada, where CLT represented 57% of the impacts and lumber production and forestry accounted for 30% and 13%, respectively (Structurlam 2013). While the allocation of impacts amongst life cycle stage are relatively similar between the Canadian and Oregon CLT GWP results, the total GWP is not. The main reason for these differences is in the primary energy consumption between Canadian production operations and Oregon. Oregon forestry practices are more intensive, using more site-preparation and harvesting methods (Oneil and Puettmann 2017). Oregon CLT is produced from a denser wood species that requires more energy to transport, saw, and dry. In addition, the Canadian

TABLE 5. Cradle-to-gate LCIA results for 1 m^3 of CLT.

Impact category	Unit	Total	CLT Manuf.	Lumber Production	Forestry Operations
	Mass Allocation Approach				
Global warming	kg CO_2 eq	158.67	97.06	42.71	18.91
Smog	kg O_3 eq	1.72	0.80	0.52	0.41
Acidification	kg SO_2 eq	0.09	0.04	0.02	0.02
Eutrophication	kg N eq	30.90	9.66	10.61	10.63
Ozone depletion	kg CFC-11 eq	1.75E-06	1.73E-06	9.29E-09	1.70E-08
Total energy	MJ	4,716.34	1,523.01	3,016.66	176.67
Non-renewable, fossil	MJ	2,298.80	1,499.48	622.78	176.54
Non-renewable, nuclear	MJ	20.47	20.29	0.05	0.14
Renewable, biomass	MJ	2,394.08	0.52	2,393.57	0.00
Renewable, wind, solar, geothermal	MJ	0.70	0.70	0.00	0.00
Renewable, water	MJ	2.29	2.02	0.27	0.00
Wood fiber	kg	585.30	0.00	0.00	585.30
Water	L	670.6	336.92	17.29	670.60
Solid waste	kg	18.23	3.46	0.18	18.23
	Economic Allocation Approach				
Global warming	kg CO_2 eq	206.26	116.75	57.26	32.25
Smog	kg O_3 eq	41.98	11.57	12.27	18.14
Acidification	kg SO_2 eq	2.27	0.96	0.62	0.69
Eutrophication	kg N eq	0.11	0.05	0.02	0.04
Ozone depletion	kg CFC-11 eq	0.0	2.08E-06	8.43E-09	2.90E-08
Total energy	MJ	5,839.96	1,832.03	3,706.50	301.43
Non-renewable, fossil	MJ	2,954.8	1,803.69	847.01	301.19
Non-renewable, nuclear	MJ	24.71	24.45	0.03	0.23
Renewable, biomass	MJ	2,859.65	0.62	2,859.03	0.00
Renewable, wind, solar, geothermal	MJ	0.84	0.84	0.00	0.00
Renewable, water	MJ	2.86	2.43	0.43	0.00
Wood fiber	kg	999.26	0.00	0.00	999.26
Water	L	828.68	381.20	417.99	29.50
Solid waste	kg	22.54	17.57	4.65	0.31

studies reported their results for lumber production using a mass allocation and the CLT using an economic allocation (Milota and Puettmann 2017). If results for Oregon CLT were reported in the same way, they would be lower too.

Energy calculations are from the CED impact assessment method (Table 5). Total energy for producing 1 m^3 of CLT was 4.7 GJ for mass allocation. Within the cradle-to-gate system boundary, lumber production used the most energy, around 64% of the total cradle-to-gate; CLT manufacturing consumed 32% of the total cradle-to-gate energy and forestry operations consumed 4%. Renewable biomass fuels represented the greatest proportion of energy consumed (51%) for total cradle-to-gate energy use, all in the lumber production gate-to-gate life-cycle stage. Non-renewable fossil fuels represented 49% of the total primary energy, with the majority consumed in the CLT gate-to-gate life cycle stage (65%). Non-renewable nuclear and renewable (solar/hydro/wind/etc.) represented less than 0.5% of the total primary energy. These fuels are used in the NWPP electricity grid.

Overall, the manufacturing of CLT in Oregon is around 50% energy self-sufficient, when considering the on-site use of renewable biomass for the lumber production process. The calculated GWP impact is limited to anthropogenic emissions of fossil carbon and does not include biogenic CO_2 emissions from the combustion of biomass. Therefore, a higher energy demand is reported with a low carbon impact.

There is a total of 893 kg of wood fiber consumed from cradle to gate to produce 1 m^3 of finished Oregon CLT. The wood fiber begins as a log at the forest road. When it arrives at the mill, approximately half will end up as finished rough lumber that may be used for CLT and the rest will be co-products (chips, residues, and wood fuel). On average, wood fuel represents about 22% of the co-product and is used for drying lumber (Milota and Puettmann 2017). Total wood fiber represents all the wood consumed from cradle to gate to produce 1 m^3 of CLT, including wood fuel, stickers, etc.

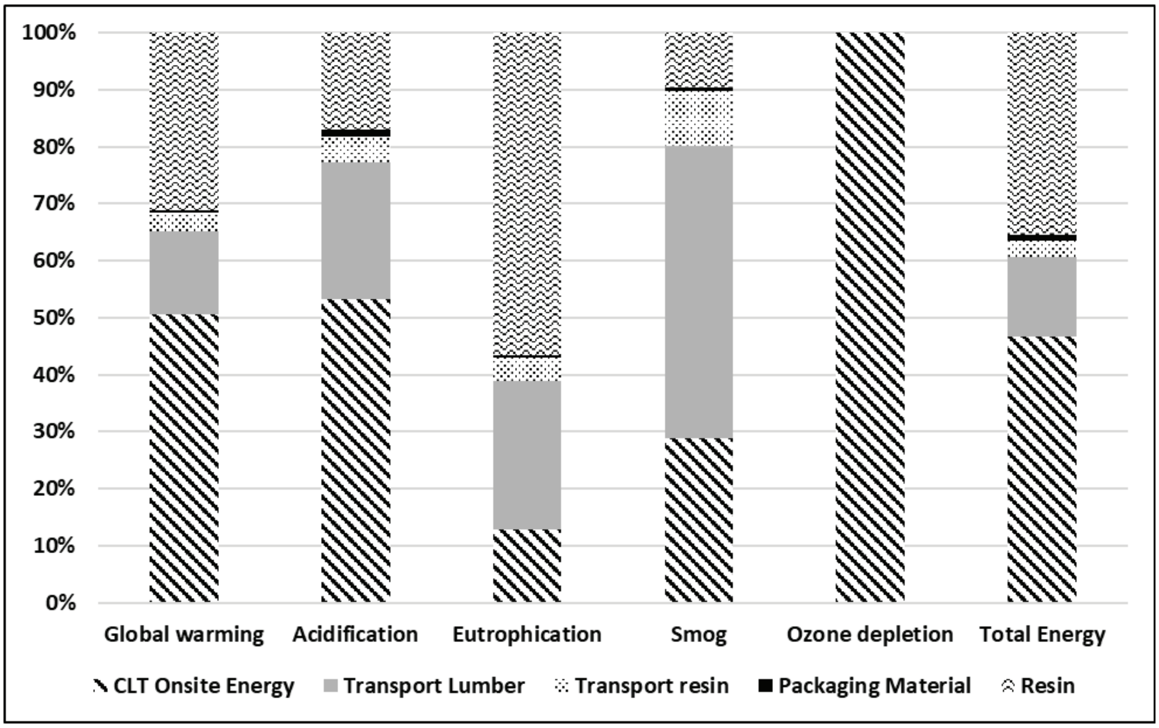
The non-renewable resources are inputs in fuel productions and electricity production used at the lumber mill and CLT plant and for resin production and transportation processes. Non-renewable resources are also inputs into the production of diesel, gasoline, natural gas, oils, and lubricants.

Water consumed (50%) during lumber production was reported as used in the log yard, where water is commonly sprayed on log decks to prevent staining and cracking of the logs. The water associated to CLT gate-to-gate production is from the resin production. Very little solid waste is generated from cradle to gate. Reported waste is packing material and "dirty" wood waste generated in the log yard.

CLT Production Gate-to-Gate LCIA Results

The gate-to-gate results include operations directly associated with the onsite production of CLT. Although economic results were higher than the mass allocation results, the relationship between the input processes in the CLT gate to gate remained constant between mass and economic allocations; this again emphasizes the impact that the lumber production process has on cradle-to-gate LCA of CLT. Five life-cycle stages were considered in the CLT gate-to-gate LCIA results: 1. energy consumed on site at the CLT facility; 2. transportation of the lumber to the facility; 3. transportation of the resin to the facility; 4. production of packaging materials for the CLT product; and 5. resin production. The percentage contribution of each life-cycle stage for the six impact categories reported is presented in Figure 3. CLT production represents about half

FIGURE 3. Gate-to-gate impact assessment results showing contribution by life-cycle stage (CLT manufacturing, lumber production, and forestry operations)(mass allocation).



of the gate-to-gate impact for GWP and acidification and nearly half of the energy consumption (47%). Onsite energy from Oregon CLT is primarily natural gas, which contributes to the GWP value and the fossil-fuel use at the CLT facility (48%). The facility was built to expand an existing cold-cure glulam process. The building itself is not well insulated; as a result, most of the fuel consumption for CLT production comes from heating the building (Table 6). The use of the MF resin accounts for 31% of the GWP and over half of the eutrophication impact for its production. Lumber transport contributed over half of the smog impact, generating from the trucking distance of 169 miles from the sawmill to the CLT facility.

Biogenic Carbon Accounting

It is known that tree growth, product production, fuel combustion, and decomposition or combustion in landfills result in various fluxes of CO_2. Carbon is emitted to the atmosphere as biomass CO_2 or fossil CO_2, depending on the fuel combusted. Carbon dioxide is also sequestered, absorbed from the atmosphere by living trees during photosynthesis. This carbon is part of the molecular structure of wood and remains in the wood of a wood product for the product's life. Cradle-to-gate carbon emissions to produce 1 m^3 of CLT were, respectively, 159 and 206 kg CO_2 eq for mass and economic allocations. That same 1 m^3 of CLT stores 985 kg CO_2 eq based on the wood content only of the finished CLT panel (537 kg), and with a carbon content of 50% (Table 7).

TABLE 6. Allocation of gate-to-gate LCIA results for 1 m^3 of finished CLT

Impact category	CLT Onsite Energy	Transport Lumber	Transport resin	Packaging Material	Resin
	Mass Allocation Approach				
Global warming	51%	14%	3%	0%	31%
Acidification	53%	24%	5%	1%	17%
Eutrophication	13%	26%	4%	1%	57%
Smog	29%	52%	10%	0%	10%
Ozone depletion	100%	0%	0%	0%	0%
Total energy	47%	14%	3%	1%	35%
Non-renewable, fossil	48%	14%	3%	1%	34%
Non-renewable, nuclear	0%	0%	0%	0%	100%
Renewable, biomass	0%	0%	0%	0%	100%
Renewable, wind, solar, geothermal	0%	0%	0%	0%	100%
Renewable, water	0%	0%	0%	0%	100%

TABLE 7. Net Cradle-to-gate carbon emissions.

	Mass Allocation	Economic Allocation
	kg CO_2 equivalent/m^3	
Forestry operations	19	32
Lumber production	43	57
CLT manufacturing	97	117
CO_2 eq. stored in product	–985	–985
Net cradle-to-gate carbon emissions	–826	–778

CONCLUSIONS

The cradle-to-gate LCA for CLT is representative of CLT production and energy inputs for the specific Oregon CLT manufacturing facility surveyed for the study. Both economic and mass allocation approaches were reported. Under the economic allocation approach, 100% of the CLT manufacturing impacts and upstream inputs were assigned to the CLT product. When using the mass allocation approach, 83% of the onsite and upstream burdens were assigned to the CLT product (cradle-to-gate). For lumber inputs, the mass allocation approach yielded lower impact values. In our LCA assessment of CLT, this was significant when lumber production allocations were changed from 50% to 86% for mass and economic allocation approaches, respectively. The impact this had on the cradle-to-gate LCA of CLT product is that under a mass allocation approach, 50% of the upstream burdens are transferred to CLT, while an economic approach increases that burden to 83%.

The CLT manufacturing stage drives most of the environmental impacts from cradle to gate. This is primarily due to resin production for CLT and the onsite energy consumption, primarily natural gas. Softwood lumber production consumed most of the energy used for drying the lumber. Life-cycle impact categories are mostly driven by the type of fuel used and whether the fuel is non-renewable or renewable. Lumber production (gate-to-gate) used nearly 100% of the heat energy, with self-generated biomass fuels for kiln operation, while fossil fuels remained the main energy source during CLT production. Wood waste was generated during CLT manufacturing (~17% of input material) and was used for energy at on offsite lumber mill (not associated with CLT manufacturing), or it was sold to a particleboard manufacturing facility offsite and used as a wood feedstock. No wood waste was burned on site or sent to a landfill.

In this study, CLT manufacturing contributed the greatest amount to the global warming impact category, while the softwood lumber production stage consumed the most energy. Natural gas use was the main contributor to the GWP value for CLT, while biomass represented 75% of the energy for lumber production (cradle-to-gate). Reducing the amount of natural gas used at the CLT manufacturing would lower the cradle-to-gate carbon footprint. Carbon was released as CO_2 during all life-cycle stages. Cross-laminated timber stores 985 kg CO_2 eq. and releases from cradle-to-gate 206 and 159 kg CO_2 eq for economic and mass allocation, respectively. The production of Oregon CLT from cradle-to-gate has a negative carbon emission of 784 kg CO_2 eq. Oregon CLT stores more carbon in the final product than is emitted during cradle-to-gate production.

Resin production also has a significant contribution to the GWP and the eutrophication impact categories for use in CLT. In these two impact categories, resin contributed 31% and 57% to GWP and eutrophication, respectively.

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