Cradle-to-Gate Life-Cycle Impact Analysis of Glued-Laminated (Glulam) Timber: Environmental Impacts from Glulam Produced in the US Pacific Northwest and Southeast*

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Abstract

This study was an update on the 2000 life-cycle inventory data on material and energy inputs associated with the production of 1 m^3 of glued-laminated (glulam) timbers produced in the Pacific Northwest (PNW) and the Southeast (SE) regions of the United States. This article looks at the cradle to gate for the entire glulam production processes, which include forest harvest, lamstock production, and glulam beam production. Data collected from glulam beam manufacturers in 2013 allowed for the development of a life-cycle assessment utilizing the product category rules for North American Structural and Architectural Wood Products so that the results from these analyses can be used for the development of environmental product declarations of glulam beams produced in the United States. Comparing the results of this study with the life-cycle assessment based on the 2000 survey data shows 30 percent reductions in global warming potential of glulam beams produced in both the PNW and the SE and reductions in the use of energy derived from fossil fuels by 40 percent in the PNW and SE. The overall net carbon sequestered in 1 m^3 of PNW glulam is equivalent to 938 kg of CO_2 and 1,038 kg of CO_2 in the SE. Utilizing techniques that reduced the use of electricity and minimizing the transportation distances of the raw materials and resins to the mill could help to further reduce the carbon footprint of the glulam beam manufacturing process.

The environmental impacts of wood products manufactured in the United States is directly related to the specific product under consideration, the exact process and raw materials utilized to manufacture the product, and the region of the country where the product is manufactured. Data to back up claims of environmental impacts help provide an approximate measure of emissions to the air, water, or ground/soil. These types of data can then help to verify if wood-based materials have less of an impact on the environment relative to similar nonwood materials. Softwood glued-laminated timbers, also known as glulam beams, manufactured in the Pacific Northwest (PNW) and Southeast (SE) regions of the United States, are one type of wood-based product where data have been collected to help

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substantiate environmental performance. Both a previous model inventorying the glulam production process from gate (lumber and resin inputs) to gate (glulam wrapped for shipment) (Puettmann and Wilson 2004, 2005) and a subsequent model from cradle (seedling) to gate (wrapped glulam) (Puettmann et al. 2013a, 2013b) utilized glulam data collected in 2000. This report provides an updated cradle-to-gate life-cycle inventory (LCI) for 2013 based on the environmental impacts associated with producing 1 m^3 of glulam wrapped and ready for shipment in both regions.

Background

Glulam is an engineered, stress-rated structural building material that typically is made of two or more layers of lumber (lamstock) that are glued together where the laminations are oriented parallel to the length of the beam or column. The lamstock is joined end-to-end, edge-to-edge, and face-to-face so that the size of a glulam is limited only by the capabilities of the manufacturing plant and/or the transportation system. Glulam produced by APA—The Engineered Wood Association members are certified with an APA EWS trademark and are tested for compliance with ANSI/AITC Standard A190.1-2012 (American Institute of Timber Construction 1983) to verify quality in product manufacturing.

Glulam markets have continued to grow as more residential construction is adopting their use. In 2016, 606,452 m^3 (257 million board feet) of glulam beams were produced. This was a 2.2 percent increase over the 2015 production volume of 593,474 m^3 (251.5 million board feet) (J. Elling, personal communication, 2017). Glulam is typically used in building systems as concealed or exposed structural beams and columns in residential and commercial construction. Glulam comes in a variety of sizes with its production based on a volume, typically board feet (1 board foot = 0.0024 m^3), and is sold by retailers on a linear foot basis. Approximately 52 percent of the glulam produced in the United States is used in the new residential housing and the remodeling construction segments, followed by nonresidential construction (37%) and industrial end uses (11%) (APA 2014). Glulam can be manufactured from any wood species as long as its physical properties allow it to be properly glued together. In the PNW region, glulam is typically made from Douglas-fir (*Pseudotsuga menziesii*), with the balance coming from Alaska yellow cedar (*Cupressus nootkatensis*) and Port Orford cedar (*Chamaecyparis lawsoniana*). In the SE region, glulam is typically manufactured from southern pine species, including longleaf (*Pinus palustris* Mill.), shortleaf (*P. echinata* Mill), loblolly (*P. taeda* L.), and slash (*P. elliottii* Engelm.) pine.

Glulam manufacturing facilities are located primarily in the PNW and the SE regions of the United States. The locations of larger manufacturers are usually close to the lamstock source so that most of the raw material inputs can arrive by truck. The glulam industry produced 542,740 m^3 (230 million board feet) of glulam in the United States in 2013 (the time of this study) (APA 2014). The volume of glulam beams manufactured by the mills that participated in the survey for this study was 373,012 m^3 (158 million board feet) or approximately 68.7 percent of total US production. Manufacturers in the PNW produced 270,029 m^3 (114.4 million board feet), or 49.7 percent of the total US output, while manufacturers in the SE produced 102,983 m^3 (43.6 million board feet), or 19.0 percent of total US production. Most glulam plants have been in operation for 20 years or more and typically utilize one of two laminating technologies: cold curing (CC) (where no added heat is used to cure the resin) or radio-frequency (RF) curing. Emission control devices are required at these facilities because toxic gases are emitted to the air from the curing of the melamine and formaldehyde resins. Besides typical air emissions from energy use and equipment combustion, wood waste is generally the main by-product of the glulam manufacturing process.

Materials and Methods

The data and analyses used for this study complied with the North American environmental product declaration protocols (FPInnovations 2015). LCI data were collected from glulam manufacturers and were used to conduct the life-cycle impact assessment (LCIA) based on TRACI, version 2.1 (Bare 2012). The LCIA data from this study can provide the basis for the development of an independent environmental product declaration. The treatment of biogenic carbon complies with the product category rules (PCRs) for North American Structural and Architectural Wood Products (FPInnovations 2015).

Goal and scope of study

The goal of this study was to update the life-cycle assessment (LCA) data for the production of glulam timbers produced in the PNW and SE regions of the United States. This study was designed to replicate the model used in the previous glulam LCA study, which was based on 2000 data (Puettmann and Wilson 2004, 2005). The two glulam LCA studies conducted by Puettmann and Wilson looked at the gate-to-gate life cycle of glulam beams, whereas this study expanded the system boundary to include the LCI of the lamstock, thereby creating a more comprehensive cradle-to-gate LCA assessment for glulam beams. The study followed the protocols recommended within the ISO 14040 and 14044 standards for conducting LCAs (International Organization for Standardization [ISO] 2006a, 2006b).

The scope of this work includes the life-cycle analyses of glulam from the PNW and SE regions of the United States from cradle (seedling) to gate (packaged product ready for shipment). Forest management and harvest data were taken from previous work conducted by Puettmann et al. (2013a, 2013b). Lumber manufacturing data for the lamstock were obtained from the recent LCI update of PNW and SE lumber manufacturers (Milota 2015a, 2015b). The glulam manufacturing data were obtained by surveying manufacturers in both regions and followed the Consortium for Research on Renewable Industrial Materials (CORRIM) protocols for performing an LCI of wood products (Puettmann et al. 2014).

System boundaries

When collecting data for an LCI, the system boundaries are defined, and the inputs and outputs into each system process are shown by the material flows within the production system (Fig. 1). Inputs and outputs for the different production stages (forest resources, lamstock manufacturing, and glulam manufacturing) are measured separately because each production stage is usually performed by a different organization. The forest resources

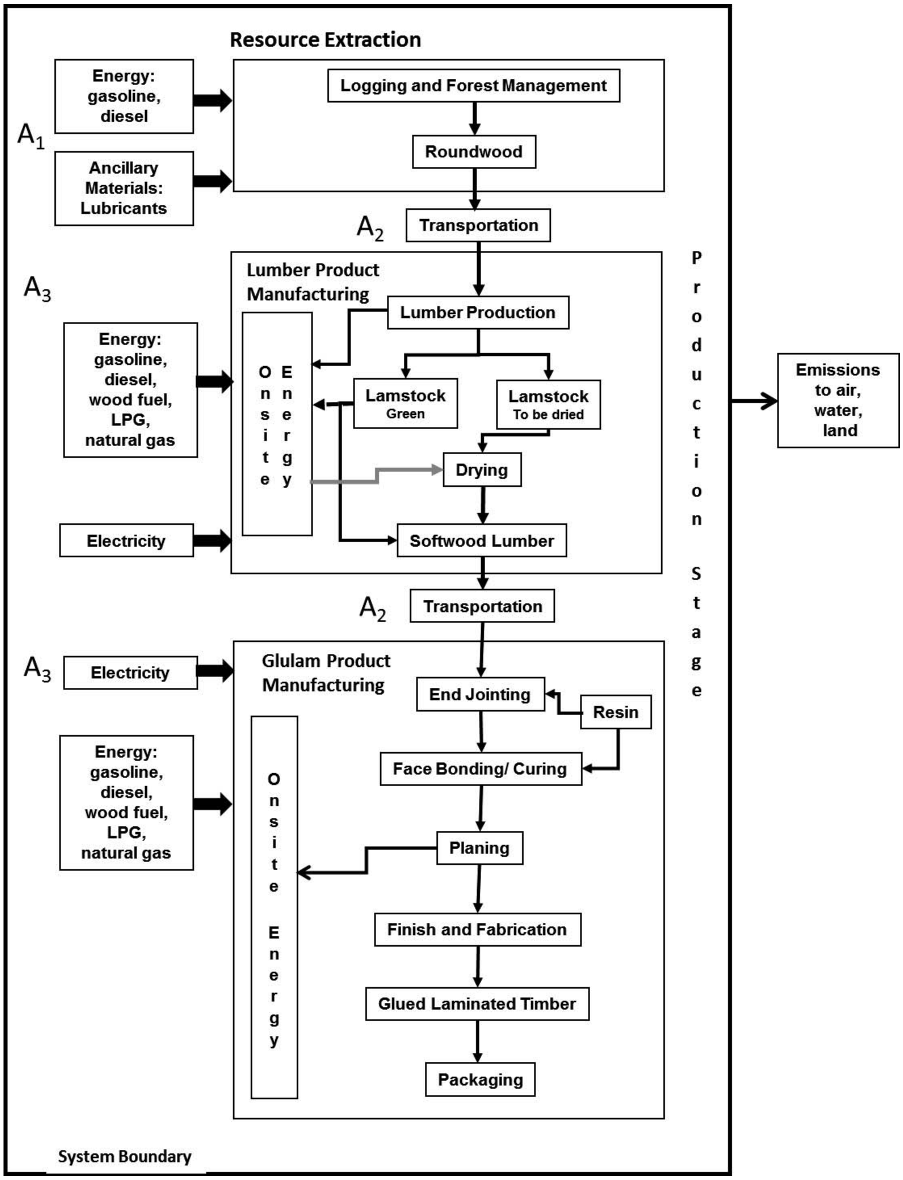

Figure 1.—Cradle-to-gate life-cycle stages for glued-laminated (glulam) timber in the Pacific Northwest and Southeast.

system boundary is considered the extraction module (A_1) for the main raw material input (logs). This includes forest regeneration and stand management operations. Seedlings and the fertilizer and electricity required to grow them were specified inputs to the system boundary. Excluded from the extraction module are the maintenance and repair of equipment and the building and maintenance of logging roads, logging camps, and weigh stations. The transportation modules (A_2) are the intermediary process between material outputs from one phase to the inputs of the next. The transportation of logs from the woods to the lumber mill and lamstock from the lumber mill to the glulam manufacturing facility are accounted for in the transportation module (A_2) (Fig. 1). Lamstock and glulam manufacturing are considered production modules (A_3) that include all the lamstock (Milota 2015a, 2015b) and glulam manufacturing processes. Some of the on-site energy generation for the lamstock gets utilized in the lumber drying process (Fig. 1). The glulam manufacturing process was modeled using a single unallocated unit process. Energy inputs for each individual process for glulam manufacturing were not measured separately owing to technology constraints of the manufacturers. The glulam process finishes at the packaging stage prior to shipment. Outputs to the entire system boundary include 1 m^3 of glulam wrapped and ready to be shipped as well as the accompanying air and water emissions, solid waste and coproducts, and waste generated from all three modules. The coproducts are no longer tracked once they leave the system boundary.

System processes.—Details for each of the main production stages provide information on how the data were obtained for the LCI model while also helping to eliminate uncertainties with the primary and secondary data utilized within the model. The cradle-to-gate LCA of glulam consisted of three main life-cycle stages: forest operations, lumber and lamstock production, and glulam production. Material and energy inputs through these stages were allocated by mass so that results could be compared with the previous data. Economic allocation results are also presented because PCRs required an economic allocation approach when a multiple-output process has differences in value of more than 10 percent.

Forest resource operations

The forestry operations section of the LCI model includes the growing of seedlings, site preparation, planting, fertilization, and final harvest, which varies for each region (Johnson et al. 2005). Assumptions about management activities were based on three levels of management intensity (low, medium, and high) in the PNW and SE with the total yield (log volume per hectare) being 501 m^3 in the PNW and 236 m^3 in the SE (Puettmann et al. 2013a, 2013b). These values were used to carry forward environmental burdens of reforestation on a per-cubic-meter basis. Most of the harvested volume comes from forest operations on private lands where investment in timber is the precursor to harvest. All raw materials (logs) taken from forests were from plantations in these two regions. Natural forest stands were not considered for this study. Harvested lands are reforested for the next crop cycle with the sequence of treatments from planting to harvest averaging 45 years in the PNW and 27 years in the SE (US Department of Agriculture Forest Service 2000; J. Mills, personal communication, 2001). Harvesting includes felling, skidding, processing, and loading the logs obtained from both commercial thinning and timber harvest operations. Inputs to the forest resources management LCI include seeds, the electricity used during greenhouse operations, the fertilizer used during seedling production and forest stand growth, and the fuel and lubricants needed to power and maintain the equipment used for site preparation, fertilization, and harvest operations. The primary output for this stage of the analysis is a log destined for the sawmill. The slash remaining (tips and limbs) was piled, and the fuel consumption for that activity is part of the regeneration stage (Oneil and Puettmann 2017). The fate of the slash piles is outside the scope of this study. Primary transportation consists of hauling the logs from the woods to a sawmill, and this transport is included in the LCI for the primary manufacturing facility (A_2) (Fig. 1). Forest operations LCI data were derived from previous studies as inputs into the lamstock manufacturing stages (Johnson et al. 2005; Puettmann et al. 2013a, 2013b).

Lamstock manufacturing

After transportation from the forest, the logs are unloaded, scaled to measure volume, and stored in log decks on the sawmill site before being transported to the sawmill. Water is sprayed on the logs to prevent them from drying out and developing blue stain (Milota 2015a, 2015b). Inputs typically include some combination of gasoline, diesel, and electricity. The outputs from this process are logs that have not been debarked. Forklifts and/or lift trucks transport the sawlogs to the debarker to begin the lamstock production process. Lamstock production is similar to lumber production in both regions (Milota 2015a, 2015b). It starts at the front end of the sawmill and includes debarking the logs, sawing the logs into green lamstock, chipping the residuals from the logs for use as coproducts (fuel for an on-site boiler, etc.), sorting the green lamstock into size and quality classes, and stacking the graded green lamstock for kiln drying. The lamstock is transported unplaned (rough) either green (greater than 19% moisture content) or kiln dried to the glulam production facility. Inputs in this module include logs with their bark, electricity, and potentially on-site power and steam generation from a boiler. Outputs from this module include green lamstock, green sawdust, green chips, bark, and green fuel wood (Milota 2015a, 2015b).

Green lamstock must be kiln dried to a moisture content of approximately 16 percent or less to minimize any additional dimensional changes before it can be used to manufacture glulam. Lamstock that exceeds the moisture content limit is redried; otherwise, the different layers of the glulam beam will not properly adhere to each other in the final glulam beam. Visual grading of the lamstock looks for any apparent flaws in the lamstock, while machine e-rated lamstock is graded by both its stiffness and its visual characteristics (American Institute of Timber Construction 1983, Western Wood Products Association 1994). This e-rated lamstock is typically required for the tension (bottom) lamination of a glulam beam that will take on the highest proportion of the bending stress when the beam is subjected to a bending load.

Resins

Two resins were utilized in the laminating and finger jointing of lamstock during the glulam beam layup and curing process: phenol-resorcinol-formaldehyde (PRF) and melamine-urea-formaldehyde (MUF). The life cycle of resins includes the raw materials, manufacturing, and transportation to the glulam facility. The PRF and the MUF LCI data used in this study are based on the data collected from resin manufacturers in 2005 (Wilson 2009).

Glulam manufacturing

Lamstock (either dried or green) is transported to the glulam manufacturing plant. The actual glulam manufacturing process can begin once the lamstock has reached the appropriate moisture content. In addition to the lamstock, the PRF and MUF resins are the only other raw material input at this stage. Glulam beams are typically manufactured in lengths that are longer than the length of the lamstock lumber obtained from the sawmills. To produce longer glulam beams, the ends of the lamstock are finger jointed so that the lumber can be joined together end to end. The glued finger joints are cured using RF curing. The RF curing process cures and stabilizes the glue bond between the pieces using a combination of pressure and heat. Continuous RF curing systems are used for finger jointing the lamstock into long lengths in both regions. This method helps to quickly process the lamstock into the longer lengths required for the glulam beams.

For face bonding, glulam production plants use both RF drying and CC processes to cure the resin. During the face bonding process, the finger-jointed lamstock is planed, and resin is applied to the face of each lamstock using a glue extruder. The lamstock is then assembled into the required layup for the specific type of beam being produced and placed in a form or press, and then pressure is applied using either the RF or the CC process. Once the resin in the beam has cured, it is removed from the presses, and all four sides are sanded or planed to remove the adhesive that was squeezed out during pressing. Each glulam beam is then individually wrapped for protection before shipping. Final product density for PNW glulam, excluding resin, averages 546 kg/m^3 at 13 percent moisture content while glulam in the SE region averages 626 kg/m^3 at 14 percent moisture content. Survey respondents in the PNW indicated that both RF (17%) and CC (83%) processes are used for glulam production, whereas 100 percent of SE glulam production utilized the RF process.

Declared unit

This study aligns itself with the PCR for ''North American Structural and Architectural Wood Products,'' UN CPC 31, NAICS 321, developed by FPInnovations (2015). A declared unit, as defined within the PCR for glulam timbers, is 1 m^3 of final product packaged for shipment. A declared unit is utilized when the function and reference scenario for the whole life cycle of a wood building material cannot be stated (FPInnovations 2015). Unit conversions for the US industry standard measure of 1 board foot = 0.0024 m^3. Inputs and outputs were allocated to the declared unit of the product based on the mass of the product and coproducts in accordance with ISO 14040 and 14044 standards (ISO 2006a, 2006b).

Data quality

The forest management and harvesting LCI data used in this study were derived from earlier studies of forest operations in the PNW and SE (Johnson et al. 2005). The data included a weighted average of various harvesting and forest management methods based on the specific forest type. The forestry systems for each region were weighted to represent a common forestry system for cellulosic fiberboard production. Lamstock manufacturing data was collected from sawmills in the PNW and SE (Milota 2015a, 2015b).

Primary glulam manufacturing data were collected from glulam mills located in the PNW and SE. The mills provided production data for 2013. Information gathered for this study included all material inputs (lamstock, resins, and packaging), water, electricity and fuel use (including transportation), and emissions. Unit process inputs for the glulam mills located in the PNW and the SE are listed in Table 1. Qualtrics Online Survey Software, version 11 (Qualtrics Labs, Inc. 2014), was utilized to conduct the survey online to reduce errors and streamline data input for analysis. Two surveys were collected manually on-site to help gather data and to allow for the verification of the data. Four mills from the PNW (49.75%) and two mills from the SE (19%) volunteered to participate in the survey, representing 68.75 percent of the total US glulam production in 2013. This total accounts for a majority of the commercially available beams produced in the United States (representative of an average product obtainable in the marketplace).

Lumber inputs were provided in board feet (Milota 2015a, 2015b) and converted to actual volumes based on the reported mix of dimension lumber brought in to each mill. PNW and SE lumber was purchased as lamstock.[1] The

Table 1.—Unit process inputs and outputs as entered into SimaPro for the production of 1 m^3 of glued-laminated (glulam) timber in the Pacific Northwest (PNW) and Southeast (SE).

	Unit/m^3	PNW	SE
Products			
Glulam	m^3	1	1
Glulam (kg)	kg	511	590
Coproducts (sawdust, shavings, trimmings)	kg	71.90	85.03
Materials/fuels			
Electricity, at grid	kWh	71.26	84.52
Natural gas	m^3	0.0534	4.52
Diesel	liters	0.94	0
Liquefied petroleum	liters	2.48	0
Gasoline	liters	0.0858	0
Wood waste combusted in boiler	kg	25.46	24.83
Transport, total	t·km	162.10	169.41
Transport, truck	t·km	110.40	169.41
Transport, rail	t·km	51.70	0
Melamine-urea-formaldehyde resin	kg	1.47	4.31
Phenol-resorcinol-formaldehyde resin	kg	7.73	0
Sawn lumber, rough, kiln dried	m^3	1.16	1.14
Sawn lumber, rough, green	m^3	0	0
Wrapping material—packaging	kg	4.19	4.95
Strapping—packaging	kg	0.19	0.32
Spacers—packaging		0	0
Emissions to air			
Particulates: unspecified	kg	0.0592	0
Volatile organic compounds	kg	0.0522	0.0433
2-Proponol	kg	0	0
Ethanol	kg	0	0
Acetaldehyde	kg	0	0.0004
Methanol	kg	0	0.0345
Phenol	kg	0.6129	0
Formaldehyde	kg	0.0241	0
Hazardous air pollutants	kg	0.3426	0

weight of the wood input was determined by converting board feet[2] (nominal) to cubic feet (actual) and then utilizing a species-specific gravity and volume at the moisture content reported during production. An actual-to-nominal ratio was then calculated based on the average percentage of each size beam produced. The LCA results will account for actual output volumes instead of nominal. All data from the survey were weight averaged based on a particular mill's production in comparison to the total survey production for the region that year. All conversion units for forestry and forest products were taken from Briggs (1994).

Assumptions

Procedures for data collection, analysis, and the formulation of assumptions followed guidelines as defined in ''CORRIM Guidelines for Performing Life Cycle Inventories on Wood Products'' (Puettmann et al. 2014) and ISO 14044 standards (ISO 2006b).

1. All flow analyses of wood through the system were determined on an ovendry weight basis with a weighted

[1] Lamstock is defined as a special grade of wood used in constructing laminated beams. In this study, lamstock was cut to 1.73 by 3.75 inches, 1.73 by 5.875 inches, 1.73 by 7.75 inches, 1.73 by 9.75 inches, and 1.73 by 11.75 inches.

[2] One board foot (BF) nominal = 0.05 cubic feet (CF) actual; 1 CF (actual) = 19.02 BF (nominal).

production density of 511 and 590 kg/m^3 for the PNW and the SE, respectively.
2. Assumptions were made for the extraction of the wood resource based on the CORRIM forest resource model (Johnson et al. 2005). Forest resource harvest and operations data were based on averages for the region.
3. Similar technology and geographic regional data were used for lamstock production, which was assumed to be the same as dried rough lumber production.
4. Primary data regarding resin production were taken from Wilson (2009). Impacts related to resin production are included in the analyses.
5. Handling of biogenic carbon follows the PCRs for North American Structural and Architectural Wood Products (FPInnovations 2015) and is consistent with the Intergovernmental Panel for Climate Change inventory reporting framework (IPCC 2006). Emissions related to biogenic carbon are not a part of global warming potential (GWP) in this study because impacts are measured only from cradle to gate.
6. Mass balance calculations were implemented to follow wood inputs and outputs within the glulam production stage. This helped to validate quality and comparability of the data.
7. Data available in the US Life Cycle Inventory database were used when available.

Impact category method

To calculate various impact categories, SimaPro, version 8.0 (Pré Consultants 2015), was utilized for data input and analyses. The TRACI 2.1, version 1.01, impact method (Bare 2012) was used to quantify the environmental impacts of forest operations, lamstock production, and glulam manufacturing. Fuel consumption was calculated per seedling and then multiplied by the number of planted seedlings per unit area specified for management scenarios in the PNW or SE (Johnson et al. 2005) to determine fuel consumption rates per unit area. Total fuel consumption per unit area was divided by the final harvested volume per unit area to establish the contribution of fuel consumption for site preparation, seedlings, and planting per unit of harvested volume. Heat released from equipment or machinery used during forest operations was not measured or reutilized and was released to the atmosphere. In manufacturing facilities, some heat was captured and reutilized at the facility.

Sensitivity analysis

A sensitivity analysis was completed per ISO 14040 standards utilizing SimaPro to show the effects of using mass allocation methodologies to measure environmental impacts versus economic allocation methodologies. Mass allocation is presented for all primary energy and emissions and was used for comparison with previous data (Puettmann et al. 2013a, 2013b). The economic allocation method is required by the most recent version of the North American Forest Products Environmental Product Declaration standard (FPInnovations 2015). Table 2 provides the allocation percentage for the PNW and SE by mass and economic value. Lumber and glulam have more economic (market) value than the coproducts manufactured during the sawmill process. The economic allocation method will distribute the environmental burdens from system processes to end products based on the proportion of their economic value to each other (in US dollars).

Table 2.—Economic allocation versus mass allocation for US-produced glued-laminated (glulam) timber.

	Pacific Northwest		Southeast	
	Mass (%)	Economic (%)	Mass (%)	Economic (%)
Glulam process				
Glulam	88.00	100.00	87.00	100.00
Coproducts	12.00	0	13.00	0
Total	100.00	100.00	100.00	100.00
Lamstock process				
Lamstock, rough green	50.10	85.98	52.20	84.16
Chips, green	24.40	11.48	30.70	14.17
Bark, green	6.10	0.61	2.60	0.25
Hog fuel, green	13.80	1.37	4.80	0.47
Sawdust, green	5.60	0.56	9.70	0.95
Total	100.00	100.00	100.00	100.00

Results

Product mass balance

The mass balance of inputs and outputs in the glulam manufacturing process is presented in Table 3 for both the PNW and the SE regions. The wood and resin used in the production of 1 m^3 of glulam during the manufacturing process results in either glulam, shavings from planing the glulam, trimmings from the ends of the glulam, or wood waste or scrap. Unaccounted inputs are assumed to be lumber at the facility from the previous year.

If the mass flow of a particular input is less than 1 percent of the cumulative mass of the model flow, it may be excluded, provided that its environmental relevance is minor. Raw materials used in small quantities that make up less than 1 percent of the product mass (excluding packaging) were not included in the LCI. These included sealer, epoxy, stain, and patching compound that were utilized when needed.

Energy requirements

Nonrenewable energy use in the PNW region consisted mainly of electricity generated from natural gas, with most of the energy in the SE coming from coal. The majority of the raw material energy consumption occurs during the glulam production stage with only a small portion arising from forestry operations. The lamstock production process also uses a considerable amount of energy, but owing to mass allocation, some of this energy is allocated to other outputs (coproducts) during the lamstock production process. Lamstock production generates most of its own energy from burning wood waste in a boiler and relies less on fossil fuel inputs. All energy used during primary transportation is assigned either to the transport of logs to the sawmill or to the transport of lamstock, resins, or packaging to the glulam mill. A wood boiler was used during lamstock and glulam production. The boiler processes utilized data from the CORRIM model for wood combusted at the boiler and for wood combusted from self-generated waste at the mill (Puettmann and Milota 2017). Only self-generated waste was used at the glulam

Table 3.—Mass balance of glued-laminated (glulam) timber manufacturing per 1 m^3 in the Pacific Northwest (PNW) and Southeast (SE).

	PNW			SE		
	Ovendry kg	Mass (%)	CoVw (%)[a]	Ovendry kg	Mass (%)	CoVw (%)
	Inputs			Inputs		
Feedstocks						
Lamstock	559.02	95.82	4.16	620.00	91.45	43.88
Unaccounted-for inputs (lumber)[b]	15.52	2.66		53.66	7.91	
Additives						
Phenol-resorcinol-formaldehyde resin	5.97	1.02	47.56			
Melamine-urea-formaldehyde resin	1.19	0.20	68.55	3.12	0.46	3.18
Catalyst/fillers/extenders	1.68	0.29	41.20	1.19	0.18	1.21
Total additives	8.84	1.52	23.10	4.31	0.64	4.39
Total inputs	583.38	100.00		677.97	100.00	
	Outputs			Outputs		
Products						
Glulam	510.70	87.54	0.47	590.00	87.02	0.00
Coproducts						
Shavings	29.71	5.09	135.12	85.00	12.54	6.54
Trimmings	42.21	7.24	62.76			
Waste	0.76	0.13	0.00	2.97	0.44	11.61
Total coproducts	72.68	12.46	39.25	87.97	12.98	9.86
Total outputs	583.38	100.00		677.97	100.00	

[a] CoVw = coefficient of variation for the weighted average of inputs and outputs. PNW: four responses; SE: two responses.
[b] Unaccounted-for inputs are assumed to be lumber on-site prior to the year of the survey.

manufacturing stage in the SE, while some purchased wood fuel was utilized in the PNW.

Transportation

Lamstock for glulam production is transported by rail or truck. The LCA incorporated an appropriate diesel tractor-trailer and diesel locomotive LCI from the US Life Cycle Inventory database (National Renewable Energy Laboratory 2012) based on transportation distances and the mass of logs used at each mill location. Some of the glulam production facilities were located next to or near lamstock facilities, thus minimizing transportation distances. Other materials, such as resins and packaging materials, are brought in by truck in containers, or in some instances, resins are brought in by liquid container trucks. Table 4 shows the average one-way distances from the manufacturer to the glulam facility. There was a very small percentage of lamstock brought in by rail to the PNW from the SE for beams that could eventually be treated for exterior use.

Electricity use

The PNW utilizes electricity from the Western Electricity Coordinating Council (WECC) grid, while the SE region utilizes electricity purchased from the SERC Reliability Corporation grid. The PNW grid utilizes the fuel mix shown in Table 5. Coal, natural gas, and hydro-generated power are the three largest contributors (82% combined) to the WECC grid with about 30.2 percent of that being attributed to renewable energy sources. Coal and nuclear are the two largest contributors (77.1% combined) to the SERC grid (Table 5) with less than 6 percent being attributed to renewable energy sources.

Table 4.—One-way delivery distances to glued-laminated (glulam) timber facility (weighted average).

	Delivery distance (km)	
Material delivered to facility	Pacific Northwest	Southeast
Dry lamstock, truck	173	234
Dry lamstock, rail	3,493	0
Resin	224	644
Strapping	390	127
Wrapping material	486	267

LCI analysis

LCI is required per ISO 14040 guidelines when completing an LCA. The LCI results for glulam are presented by the three life-cycle stages: (1) forestry operations, (2) lamstock production, and (3) glulam production (Tables 6 and 7). The majority of fossil fuel consumption for energy production occurs during glulam

Table 5.—Electricity grid mix for 2008 in the Pacific Northwest and Southeast.[a]

Grid generation mix	WECC (%)	SERC (%)
Natural gas	29.4	16.0
Hydro	22.3	4.4
Coal	30.3	51.3
Nuclear	9.9	25.8
Biomass	1.3	1.8
Wind	3.4	<0.1
Petroleum	0.2	0.6
Other renewables	3.2	0.1
Total	100.0	100.0

[a] According to the National Renewable Energy Laboratory (2012). WECC = Western Electricity Coordinating Council; SERC = SERC Reliability Corporation.

Table 6.—Energy usage per 1 m^3 of glued-laminated (glulam) timber in the Pacific Northwest (PNW) and Southeast (SE) (mass allocation).

Fuel	PNW				SE			
	% mix	Forestry (MJ/m^3)	Lamstock (MJ/m^3)	Glulam (MJ/m^3)	% mix	Forestry (MJ/m^3)	Lamstock (MJ/m^3)	Glulam (MJ/m^3)
Coal, in ground	9.8	6.94E+00	2.06E+02	2.92E+02	14.9	8.89E+00	3.89E+02	6.02E+02
Gas, natural, in ground	11.2	1.33E+01	2.87E+02	2.75E+02	7.3	6.38E+01	1.30E+02	2.96E+02
Oil, crude, in ground	11.9	1.87E+02	1.92E+02	2.31E+02	9.1	2.13E+02	2.09E+02	1.86E+02
Uranium oxide, in ore	2.6	2.04E+00	5.81E+01	7.56E+01	5.3	2.56E+00	1.36E+02	2.15E+02
Total nonrenewable		2.10E+02	7.43E+02	8.73E+02		2.88E+02	8.64E+02	1.30E+03
Wood waste	62.7	0.00E+00	2.73E+03	4.81E+02	63.3	0.00E+00	3.80E+03	4.47E+02
Renewables, other	1.7	3.70E−01	2.69E+01	6.24E+01	0.2	3.20E−01	4.85E+00	9.00E+00
Total %	100.0	4.1	68.3	27.6	100.0	4.3	69.5	26.2

Table 7.—Air and water emissions released per 1 m^3 of glued-laminated (glulam) timber in the Pacific Northwest (PNW) and Southeast (SE) (mass allocation).[a]

	PNW (kg/m^3)				SE (kg/m^3)			
	Total	Forestry operations	Lamstock production	Glulam production	Total	Forestry operations	Lamstock production	Glulam production
Air emission								
Acetaldehyde	0.024	0.000	0.024	0.000	0.008	0.000	0.007	0.000
Acrolein	0.001	0.000	0.001	0.000	0.001	0.000	0.001	0.000
Ammonia	0.003	0.000	0.002	0.000	0.003	0.001	0.002	0.000
Carbon dioxide, biogenic	269.66	0.011	228.78	40.87	276.69	0.014	238.72	37.96
Carbon dioxide, fossil	111.42	14.50	43.83	53.09	140.84	16.74	50.22	73.88
Carbon monoxide, biogenic	0.493	0.000	0.419	0.074	0.500	0.000	0.431	0.069
Carbon monoxide, fossil	0.363	0.132	0.109	0.122	0.359	0.149	0.112	0.097
Dinitrogen monoxide	0.002	0.000	0.001	0.001	0.006	0.004	0.001	0.001
Formaldehyde	0.024	0.000	0.002	0.022	0.011	0.000	0.010	0.001
HAP, total	0.302	0.000	0.001	0.302	0.365	0.000	0.001	0.365
Methane	0.278	0.021	0.123	0.133	0.320	0.038	0.105	0.177
Methanol	0.020	0.000	0.020	0.000	0.075	0.000	0.045	0.030
Nitrogen oxides	0.850	0.263	0.332	0.255	0.953	0.299	0.387	0.267
Nonmethane VOC	0.035	0.009	0.010	0.017	0.032	0.010	0.011	0.011
Particulates, <10 μm	0.125	0.000	0.061	0.064	0.064	0.000	0.054	0.010
Particulates, <2.5 μm	0.029	0.000	0.025	0.003	0.061	0.000	0.058	0.003
Particulates, >10 μm	0.020	0.000	0.019	0.001	0.081	0.000	0.080	0.001
Particulates, >2.5 and <10 μm	0.018	0.008	0.005	0.005	0.019	0.009	0.005	0.005
Particulates, unspecified	0.031	0.001	0.012	0.017	0.059	0.002	0.023	0.034
Phenol	0.539	0.000	0.000	0.539	0.001	0.000	0.001	0.000
Propanal	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Sulfur dioxide	0.530	0.010	0.249	0.271	0.760	0.038	0.278	0.444
Sulfur monoxide	0.035	0.015	0.004	0.016	0.037	0.017	0.005	0.015
Sulfur oxides	0.027	0.000	0.013	0.014	0.017	0.000	0.013	0.004
VOC	0.351	0.007	0.267	0.077	1.028	0.009	0.950	0.068
Water emission								
Ammonia	0.002	0.000	0.001	0.001	0.002	0.000	0.001	0.001
BOD5	0.043	0.003	0.012	0.028	0.020	0.004	0.006	0.010
Chloride	3.601	0.614	1.484	1.503	3.375	0.851	1.043	1.481
COD	0.033	0.006	0.013	0.013	0.030	0.008	0.010	0.013
Formaldehyde	0.002	0.000	0.000	0.002	0.000	0.000	0.000	0.000
Oils, unspecified	0.003	0.000	0.001	0.001	0.002	0.001	0.001	0.001
Phenol	0.001	0.000	0.000	0.001	0.000	0.000	0.000	0.000
Phosphate	0.001	0.001	0.000	0.000	0.017	0.016	0.001	0.000
Solids, inorganic	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.001
Solved solids	1.224	0.000	1.151	0.073	0.774	0.000	0.719	0.054
Suspended solids, inorganic	0.002	0.000	0.000	0.002	0.001	0.000	0.000	0.001
Suspended solids, unspecified	3.406	0.802	0.742	1.862	3.570	1.103	0.630	1.837

[a] HAP = hazardous air pollutant; VOC = volatile organic compounds; BOD = biological oxygen demand; COD = chemical oxygen demand.

manufacturing (Table 6), followed by the production of lamstock and only a very small portion allocated to forestry operations. The highest energy use from fossil fuels in the production of glulam was natural gas in the PNW and coal in the SE (Table 6). Energy generated from wood waste represented 62.7 and 63.3 percent of the primary energy mix for the PNW and the SE, respectively, and was used for lamstock drying and on-site energy production.

Table 7 lists the total cradle-to-gate air emissions (on-site) generated as a result of the production of 1 m^3 of glulam for both the PNW and the SE region. Glulam manufacturing generates air emissions, such as CO_2 from the electricity used by equipment during the jointing, bonding, planing, and finish and fabrication stages. Air emissions, including hazardous air pollutants, are a result of resin use during face bonding and curing and particulate matter that are generated during resizing operations (jointing, planing, and finishing). Emissions to the air from formaldehyde and methanol use are required to be reported by mills and are quantified by measuring acetaldehyde, acrolein, formaldehyde, methanol, phenol, propionaldehyde (or propanal), and other volatile organic compound outputs. These are all noted as components of hazardous air pollutants. The results in Table 7 have the inventory results for air emission outputs released per cubic meter of glulam produced in the PNW and SE regions. The table presents the contribution from each of the three life-cycle stages.

Most of the water emissions generated from the glulam life cycle were from upstream processes, such as fuel and resin production. During glulam production, little water was utilized, but most of the water use was attributed to steam during additional kiln drying or steam for heat during RF curing. Other water consumption was for cleaning and general maintenance of equipment and other processes. Water emissions attributed to the production of 1 m^3 of glulam in the PNW and SE are provided in Table 7.

Life-cycle impact assessment

The LCIA phase establishes links between the LCI results and potential environmental impacts. This LCIA for glulam calculated the impact indicators shown in Table 8. These impact indicators provide general but quantifiable indications of potential environmental impacts. Energy consumption from nonrenewables, renewables (wind, hydro, solar), and nuclear fuels, water use, and solid waste are shown in Table 9. For GWP in the PNW, 48 percent of the CO_2 equivalent emissions come from producing the glulam, with 39 percent being attributed to lamstock production and 13 percent being assigned to forestry operations. For GWP in the SE, 52 percent of the CO_2 equivalent emissions come from producing glulam, with 35 percent being attributed to lamstock production and 13 percent being assigned to forestry operations. Values in Table 8 are the cumulative impact of all upstream processes required for glulam production, including those from forestry operations, lamstock production, resin used, and packaging production and the transportation energy required to ship these materials to the glulam production facility. Figures 2 and 3 provide a contribution analyses to show the percentage that each life-cycle stage contributes to each of the environmental impact categories.

There was also solid waste generated during the production of glulam beams (Table 9). Most of the wood waste was recycled or utilized as fuel for the wood boiler. Glulam mills did not report any other solid waste being generated from manufacturing processes. Solid waste included ash produced within the boiler. Other waste products generated are a result of upstream processes, primarily from the production of the fuels and resins, used in

Table 8.—Categories for life-cycle impact assessment per 1 m^3 of glued-laminated (glulam) timber output in the Pacific Northwest (PNW) and Southeast (SE) (mass allocation).

		PNW				SE			
Impact category	Unit	Total	Forestry operations	Lamstock production	Glulam production	Total	Forestry operations	Lamstock production	Glulam production
Global warming	kg CO_2 eq	119.12	15.19	47.26	56.67	151.45	19.73	53.24	78.48
Acidification	kg SO_2 eq	1.203	0.209	0.507	0.487	1.508	0.266	0.579	0.663
Eutrophication	kg N eq	0.046	0.015	0.017	0.014	0.086	0.052	0.020	0.014
Ozone depletion	kg CFC-11 eq[a]	1.33E−08	6.94E−10	1.21E−09	1.14E−08	6.67E−09	1.78E−09	1.41E−09	3.48E−09
Smog	kg O_3 eq	24.39	6.55	9.44	8.40	27.69	7.46	13.24	6.99

[a] CFC = chlorofluorocarbon.

Table 9.—Energy consumption, water usage, and waste per 1 m^3 of glued-laminated (glulam) timber output in the Pacific Northwest (PNW) and Southeast (SE) (mass allocation).

		PNW				SE			
	Unit	Total	Forestry operations	Lamstock production	Glulam production	Total	Forestry operations	Lamstock production	Glulam production
Total primary energy	MJ	5,130.88	210.04	3,504.67	1,416.17	6,708.57	288.76	4,664.88	1,754.93
Nonrenewable fossil	MJ	1,689.76	207.63	684.77	797.36	2,096.85	285.88	727.28	1,083.69
Nonrenewable nuclear	MJ	135.73	2.04	58.07	75.62	353.87	2.56	136.27	215.04
Renewables, other	MJ	88.08	0.37	26.36	61.35	9.50	0.32	3.21	5.97
Renewable, biomass	MJ	3,217.31	—	2,735.46	481.85	4,248.35	—	3,798.12	450.23
Freshwater	liters	459.25	14.17	378.68	66.40	557.20	—	452.49	104.71
Solid waste	kg	8.67	0.23	3.84	4.60	17.01	0.30	6.45	10.26

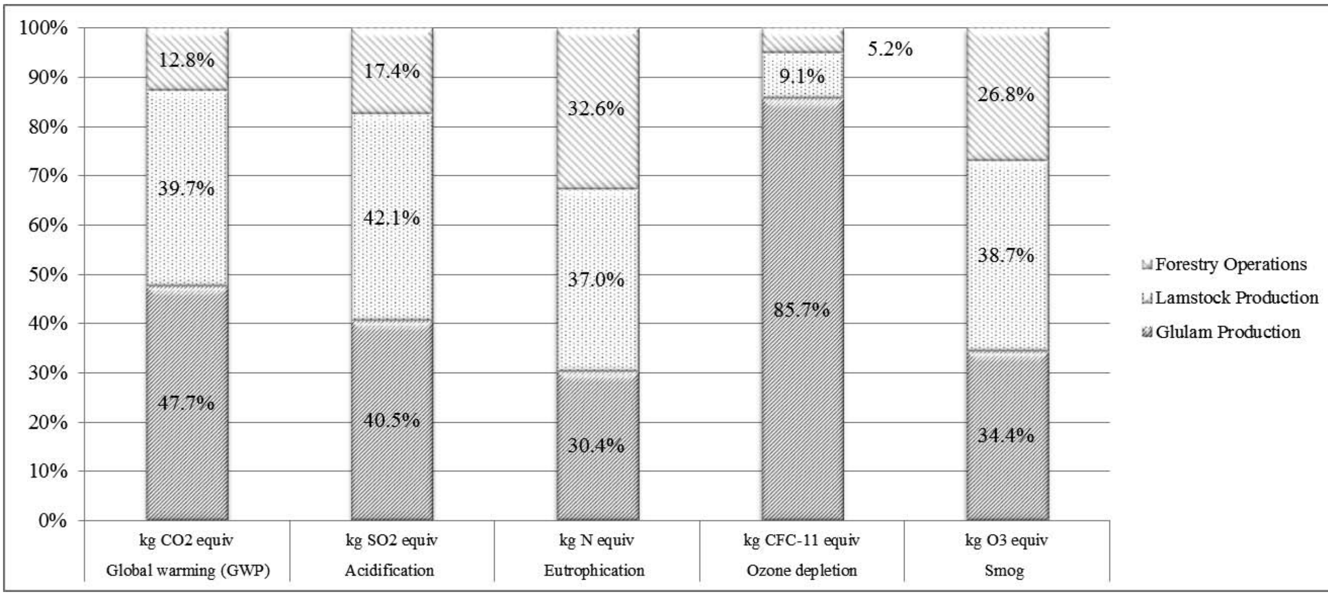

Figure 2.—Contribution analysis life-cycle impact assessment per 1 m^3 of glued-laminated (glulam) timber production in the Pacific Northwest (mass allocation).

lamstock and glulam production. In total, 8.67 and 17.01 kg of solid waste was generated from cradle to gate during the production of 1 m^3 of glulam in the PNW and the SE, respectively.

Carbon balance

The carbon balance for wood-based materials in the cradle-to-gate glulam processes are shown in Table 10. There are very few if any coproducts in the glulam manufacturing process. The table provides a comparison of the CO_2 sequestered in the final glulam at the gate compared with the total CO_2 emissions during the three-stage life cycle. Inputs include rough-sawn dried lumber (lumber manufacturing excluded). Outputs include products and coproducts as reported on the survey. Emissions related to wood combustion of purchased hog fuel are included for the PNW. One mill in the PNW and two in the SE reported boiler emissions. The CO_2 uptake for wood and bark is determined by multiplying the product process input dry

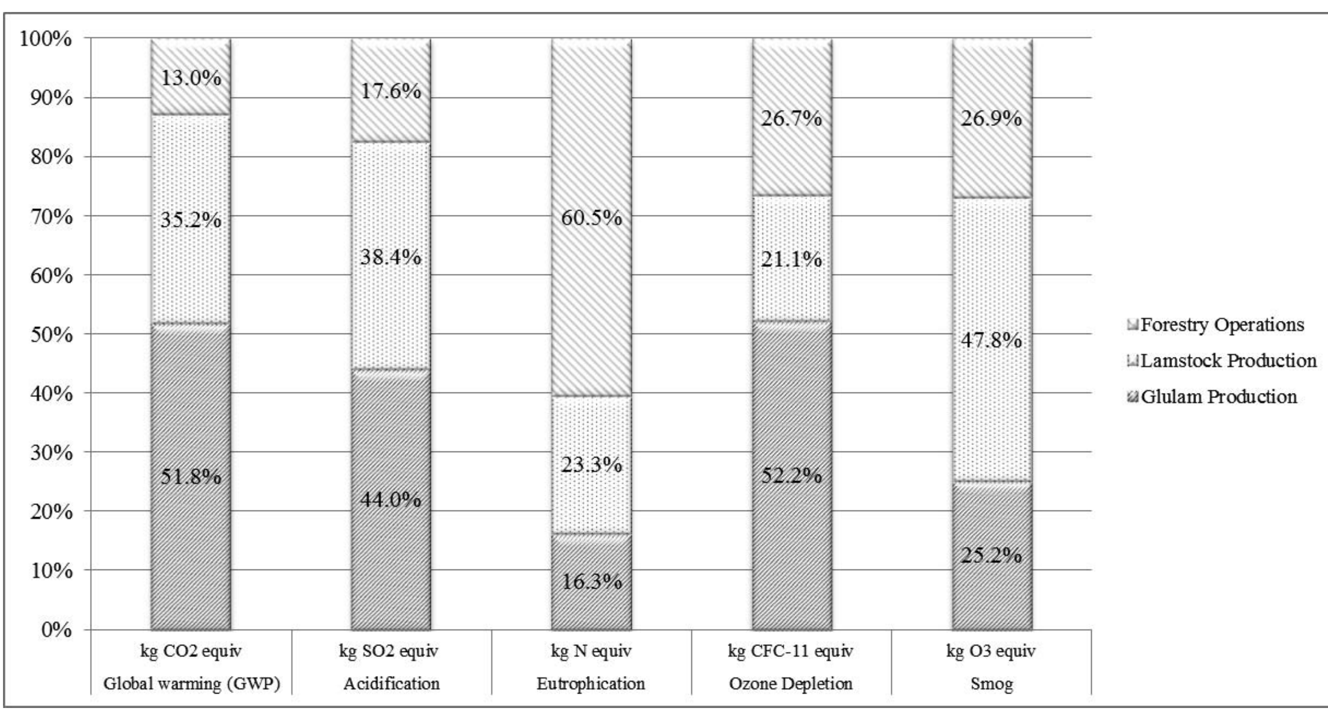

Figure 3.—Contribution analysis life-cycle impact assessment per 1 m^3 of glued-laminated (glulam) timber production in the Southeast (mass allocation).

Table 10.—Carbon balance per 1 m^3 softwood glued-laminated (glulam) timber in the Pacific Northwest (PNW) and Southeast (SE) (mass allocation).

	PNW (kg CO_2 eq)	SE (kg CO_2 eq)
Released forestry operations	15.19	19.73
Released lumber manufacturing	47.26	53.24
Released glulam manufacturing	56.67	78.48
CO_2 equivalent stored in product	937.69	1,082.65

weight of wood and associated bark in kilograms (tracked separately) by 1.83 (assuming a 50% carbon content of wood and bark), which gives the equivalent CO_2 uptakes based on the carbon content of wood and bark. This calculation is presented below. The CO_2 uptake is determined on the volume of wood and bark (dry weight basis) input to the product process:

$$\left(\frac{44\,\mathrm{g\,CO_2/kmole}}{12\,\mathrm{g\,C/kmole}}\right)\times\left(\frac{0.5\,\mathrm{kg\,C}}{1.0\,\mathrm{kg\,ovendry\,wood}}\right)\times\left(\frac{\mathrm{kg\,ovendry\,wood}}{\mathrm{m^3}}\right)$$

Changes from previous data (2000 vs. 2013)

Table 11 shows the reduction in fuel use that contributes to the large reduction in fossil fuel use. The large increase in energy from renewable biomass led to the large reduction in natural gas use because the boilers could be run with residual biomass from the mills. Respondents reported an increase in diesel and LPG use in the PNW, while in the SE, respondents did not report diesel, gasoline, or LPG use or did not track it. There was an increase in transportation in the PNW, which also increased diesel use in that region.

Table 12 shows the change in resin use and methods from the last report (2000 vs. 2013). Mills that responded to this survey produced more glulam using CC techniques (83%) since the last report (19%) in the PNW, while mills in the SE reported using only RF curing (100%), which was an increase from the last report (47%). This also translated to an increase in resin needed for CC in the PNW versus a reduction in resin use in the SE. This was another factor in the reduction in electricity use in the PNW. CC glulam uses less energy on-site, but RF curing has fewer environmental impacts upstream because less resin is needed for face bonding. Only MUF resin was reported being used in the SE for both face bonding and finger jointing of the lamstock.

A comparison of the LCIA results obtained from the two surveys (Puettmann et al. 2013a, 2013b) is shown in Table

Table 12.—Resin use and curing type comparisons of 2000 and 2013 input data per 1 m^3 glued-laminated (glulam) timber in the Pacific Northwest (PNW) and Southeast (SE) (mass allocation).

		PNW		SE	
Resin and method of cure	Unit	2000	2013	2000	2013
Phenol-resorcinol-formaldehyde resin	kg	5.17	7.73	7.96	0
Melamine-urea-formaldehyde resin	kg	0.96	1.47	0.77	4.31
Cold cure	% used	19	83	53	0
Radio frequency	% used	81	17	47	100

13. For the PNW region, the results show that there was a 29.9 percent reduction in GWP compared with the previous report. There was also a reduction in eutrophication (–45.2%) but an increase in smog potential (+20.0%) since 2000. In the SE, there were reductions in GWP (–30.7%), eutrophication (–39.4%), and smog (–7.4%) since 2000. Ozone depletion could not be determined when compared with the previous study, and the accounting method for acidification has changed since the previous report. For fossil fuel and renewable biomass use, Table 13 shows reductions in energy derived from fossil fuel use in both the PNW and the SE but increases in the energy derived from biomass (+50.5% and +92.0% in the PNW and the SE, respectively). Freshwater usage also decreased in 2013, with 43.0 and 49.0 percent reductions being reported in the PNW and the SE, respectively. There were very few if any technology changes between the two studies, but changes in energy use, supplier locations (distance to production facilities), and the electricity grid compositions likely contributed to some of the differences observed between the two reports.

Economic allocation

Three life-cycle stages were used in the overall cradle-to-gate assessment of the glulam beam production process. Their contribution to the different impact categories varies depending on whether a mass or an economic allocation is applied. Economic allocation of environmental burdens is another methodology that attaches a certain percentage of the air, water, or land emissions based on the average market value of all end products or processes at the gate. The only end products in this system process are the finished glulam and the small amount of waste and scraps that are used for hog fuel. Using the economic allocation method, intrinsic value cannot be placed on the other coproducts, and therefore 100 percent of the environmental burdens are

Table 11.—Fuel and transport comparisons 2000 and 2013 input data per 1 m^3 glued-laminated (glulam) timber in the Pacific Northwest (PNW) and Southeast (SE) (mass allocation).

		PNW			SE		
Fuels and transport	Unit	2000	2013	% change	2000	2013	% change
Electricity	kWh	84.44	71.26	−15.6	98.88	84.52	−14.5
Natural gas	m^3	3.98	0.05	−98.7	26.39	4.52	−82.9
Diesel	liters	0.36	0.94	161.1	0.66	0	NA[a]
Liquefied petroleum gas	liters	1.62	2.48	53.1	0.41	0	NA
Gasoline	liters	17.46	0.09	−99.5	0.39	0	NA
Transport	t·km	84.58	162.10	91.7	296.89	169.41	−42.9

[a] NA = not available.

Table 13.—Comparison of 2000 and 2013 life-cycle impact assessment data per 1 m^3 glued-laminated (glulam) timber in the Pacific Northwest (PNW) and Southeast (SE) (mass allocation).

	Change from previous data					
	PNW			SE		
	2000	2013	% change	2000	2013	% change
Impact indicator						
Global warming potential	169.85	119.12	−29.87	218.67	151.45	−30.74
Eutrophication	0.0839	0.046	−45.17	0.142	0.086	−39.44
Smog	20.33	24.39	19.97	29.90	27.69	−7.39
Natural resource use						
Total energy (MJ)	5,266.24	5,130.88	−2.57	6,183.87	6,708.57	8.48
Fossil fuel (MJ)	2,818.46	1,689.76	−40.05	3,514.76	2,096.85	−40.34
Renewable biomass (MJ)	2,137.65	3,217.31	50.51	2,213.25	4,248.35	91.95
Freshwater (liters)	806.16	459.25	−43.03	1,092.44	557.20	−48.99

Table 14.—Sensitivity analysis of mass allocation versus economic allocation methods.

	Pacific Northwest			Southeast		
Impact indicator	Mass	Economic	% change	Mass	Economic	% change
Global warming	119.12	134.67	13.05	151.45	172.47	13.88
Acidification	1.203	1.327	10.31	1.508	1.682	11.54
Eutrophication	0.046	0.050	8.7	0.086	0.091	5.81
Ozone depletion	1.33E−08	1.50E−08	12.78	6.67E−09	7.47E−09	11.99
Smog	24.387	26.616	9.14	27.691	29.885	7.92

allocated to the finished 1 m^3 of glulam. Table 14 shows how the allocation of burdens differed from a mass allocation methodology versus an economic allocation methodology for both glulam beams and lamstock. The forest operations process is identical using both allocation methods because the only product of value coming from the forest in this study is the harvested log. Table 14 shows how the environmental impacts change as the glulam and lamstock take more of the burdens based on their higher market value.

Conclusions

Manufacturing of wood products shows an increased use of renewable energy and a reduced reliance on nonrenewable fossil fuels when evaluating the entire cradle-to-gate LCA of glulam beams. Emissions resulting from the forest resources LCI are smaller relative to the manufacturing emissions of lamstock or glulam beams. The glulam beam manufacturing process generates some on-site emissions during the end jointing and face bonding processes, although most of the emissions are generated upstream during electricity generation. Glulam beam production represented a larger percentage of the entire system emissions than did lamstock production and consequently consumed the highest level of energy inputs. Most of the energy consumed during the glulam beam production stage in the PNW and SE regions was from the use of nonrenewable fossil fuels (56% and 62%, respectively). The total system process (forestry, lamstock, and glulam) used 62.7 percent renewable biomass in the PNW and 63.3 percent in the SE. The total energy consumption represented a larger use of renewable materials overall compared with the previous glulam LCA study conducted in 2000.

The TRACI impact method does not count the contribution of wood-derived CO_2 emissions generated from burning wood fuel in the boiler toward the global warming impact estimate. Using the TRACI method, we estimated that 119.12 kg CO_2 eq was released during the production of 1 m^3 of PNW glulam and 151.45 kg CO_2 eq during the production of 1 m^3 of glulam in the SE. That same 1 m^3 of glulam produced in the PNW stores 937.69 kg CO_2 eq, while glulam produced in the SE stores 1,082.65 kg CO_2 eq. Some carbon is released as CO_2 during all of the life-cycle stages. In summary, the LCA analysis demonstrates that glulam beams have a positive carbon balance (they sequester carbon) from cradle to gate. This information could be used to compare the environmental footprint of wood-based products with reinforced concrete or steel in a functional unit analyses. The next generation of construction practices are implementing LCA to measure entire environmental impacts of buildings, and this requires information that is provided in this study.

Recommendations for future LCA studies would be to investigate the increase in the combustion of coproducts (trimmings and shavings) for boiler fuel and estimate how this trend might affect future environmental impacts. Mills reported an increase in the use of the CC process for the face bonding of glulam in the PNW, which directly relates to the reduction in electricity use observed since the last report. There was in increase in RF curing in the SE but also a large increase in the use of renewable biomass for energy use within the mill. Analyzing the impacts of CC techniques versus those of RF curing could generate further data to determine whether a reduced amount of resin use during RF curing offsets the additional electricity it uses on-site. More frequent data collection and surveying past participants will help eliminate uncertainties in the data while attempting to account for fluctuations in the data from electricity grid and fuel changes and shifts in product demand.

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