Cradle-to-Gate Life-Cycle Assessment of Laminated Veneer Lumber Production in the United States*

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Abstract

To keep environmental product declarations current, the underlying life-cycle inventory (LCI) data and subsequent life-cycle assessment data for structural wood products must be updated. Primary data collected from the industry for the year 2012 were analyzed using the weighted-average to update LCIs for laminated veneer lumber (LVL) production on a 1-m^3 basis in the Southeast (SE) and Pacific Northwest (PNW) regions of the United States. In addition, cradle-to-gate life-cycle impact assessments (LCIAs) were performed to assess the environmental impacts associated with LVL production for both regions. The cradle-to-gate LCIAs included three life-cycle stages: forestry operations, dry veneer production, and LVL production. The LCIs revealed that the dry veneer life-cycle stage dominated overall primary energy consumption for both the SE and the PNW at 6.83 (68.5%) and 6.75 GJ/m^3 (75.3%), respectively. Energy consumption at the veneer stage was based primarily on renewable sources, especially wood fuel consumed on-site for thermal energy generation. In contrast, the LVL production stage was dependent mainly on fossil fuels, where the major resources consumed were natural gas and coal. The LCIA results showed that the veneer production stage dominated the majority of the five impact categories investigated with a greater than 50 percent contribution. Yet the LVL production stage had a significant contribution to the ozone depletion impact category, with 92 and 98 percent of total impact, for the SE and the PNW, respectively, coming from resin production used in LVL manufacturing. Overall, the contribution of forestry operations to the resulting impacts was minor.

Documenting the environmental performance of building products is becoming widespread because of many green marketing claims being made without scientific merit (i.e., green washing). Increased environmental awareness (i.e., environmental preferential purchasing) and environmental regulations that manufacturers and forest landowners face require manufacturers to assess their environmental performance and communicate environmental information. Developing environmental product declarations (EPDs) for structural wood products is one way to accomplish this objective for scientific documentation (International Organization for Standardization [ISO] 2006a, Bergman and Taylor 2011). EPDs provide objective and verified data on environmental performance of products and services and can be used to identify the environmental hot spots for improvements. In addition, keeping EPDs current allows the continuous environmental improvement of products to be assessed over time. In addition, developing wood product life-cycle inventory (LCI) data helps construct product life-cycle assessments (LCAs) that are then incorporated into developing whole building LCAs in environmental footprint software, such as the Athena Impact Estimator for Buildings (Athena Sustainable Material Institute 2016). Conducting whole building LCAs provides for points that go toward green building certification in rating systems such as LEED v4, Green Globes, and the ICC-700 National Green Building Standard (Ritter et al. 2011).

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There has been an increasing interest in engineered wood products since the 1980s. Currently, the use of wood products such as glue-laminated beams, I-joists, and laminated veneer lumber (LVL) instead of large timbers in roofing and flooring systems is increasing (Prestemon et al. 2015). LVL is an engineered wood product that falls into the North American Industry Classification System (NAICS) Code 321213, ''Engineered Wood Member (except Truss) Manufacturing,'' which includes other structural wood engineered products such as finger joint lumber, I-joists, parallel strand lumber, and glue-laminated timbers (US Census Bureau 2012, ASTM International 2014a).

LVL, which is composed of multiple layers of dry wood veneers glued together with their grain orientation in the same direction, is designed to be used in the same manner as solid wood products, such as sawn lumber (US Environmental Protection Agency [US EPA] 2002, Wilson and Dancer 2005, Stark et al. 2010). The veneers are made from rotary peeling of veneer logs. One major advantage of LVL is that it can easily be manufactured in desired size, length, and shape. It is also durable and comparable to solid timber, concrete, and steel in terms of strength and shows notable carbon emission savings (Bergman et al. 2014). LVL can be used as an alternative to structural lumber in residential and commercial construction. It can be used in conjunction with softwood plywood or oriented strandboard to make composite I-joists but could also be used as a stand-alone for headers, beams, edge-forming material, and joists (Wilson and Dancer 2005; Puettmann et al. 2013a, 2013b). In the early 2000s, LCI data for major structural wood products in the United States for different wood production regions were developed as a part of an extensive LCA effort initiated through the Consortium for Research on Renewable Industrial Materials (CORRIM 2005, 2010). Currently, the LCIs developed are publicly available through the US LCI Database (National Renewable Energy Laboratory [NREL] 2012). As a part of the earlier CORRIM initiative, Wilson and Dancer (2005) developed the LVL LCI data for the Southeast (SE) and Pacific Northwest (PNW) regions of the United States based on production data for the year 2000. Later, Puettmann et al. (2013a, 2013b) developed the corresponding regional LVL LCAs for use in developing a North American LVL EPD (American Wood Council/Canadian Wood Council 2013). The goal of this study was to update the LCI data for LVL production in the SE and PNW regions of the United States based on 2012 manufacturing data and develop new cradle-to-gate LCIs. In addition, LCAs were performed and presented using the updated inventory data for LVL manufacturing for the two regions. The two updated LVL LCA data sets will be used to update the current North American LVL EPD. Data quality requirements to develop EPDs are described in the product category rule (PCR) for North American Structural and Architectural Wood products (FPInnovations 2015). The requirements for the primary data include representativeness of the North American region in terms of geographic and technological coverage. The data typically required to be less than 10 years old. Earlier, CORRIM study LCI was based on 2000 production data, and in order to fulfill PCR requirements, updated LCI data were needed. This article presents the LCI data developed for LVL production in the United States representative of the production year 2012.

Materials and Methods

This article presents the LCI developed and the results of the cradle-to-gate LCA performed to assess the environmental impacts associated with the LVL production in the PNW and SE regions of the United States. The LCI data were generated based on the primary data collected from LVL plants in accordance with the CORRIM Research Guidelines (CORRIM 2014). Secondary data, such as supply of electricity, manufacturing of the chemicals, transport, and disposal, were from peer-reviewed literature and the US LCI database (NREL 2012). Material and energy balances were calculated from primary and secondary data. The SimaPro 8.0.5 software incorporating the US LCI Database (NREL 2012) modeled the system (PRé Consultants 2016). Complete details of this study for LCI development for LVL production and the CORRIM project can be found in Bergman and Alanya-Rosenbaum (2017a, 2017b). The LCA that was performed conformed with the PCR for North American structural and architectural wood products (FPInnovations 2015) and ISO 14044 and 14040 standards (ISO 2006b, 2006c).

Goal and scope definition

This study had two main objectives. The first objective was to develop updated cradle-to-gate LVL manufacturing LCI data. The second was to assess environmental impacts associated with LVL production in the United States by performing a cradle-to-gate LCA, focusing on two regions: the SE and the PNW. The results of this study provided information on current environmental performance of the regional LVL production in the United States. The outcomes of this life-cycle impact assessment (LCIA) study can be used by LVL plant managers and wood associations to identify potential process improvements and to enhance environmental performance of LVL production in the two regions.

In accordance with international standards (ISO 2006b, 2006c; International Reference Life Cycle Data System 2010), the scope of the present LCA study covered the life-cycle stages of LVL from forest resource activities through veneer production to the final LVL product leaving the plant. The present LCA provided a cradle-to-gate analysis of environmental impacts and cumulative energy of manufacturing and transportation of raw materials to the veneer and LVL production facilities.

Allocation procedure

Selecting an allocation approach is an important part of an LCA study. In the present study, all primary energy and environmental outputs were assigned to various coproducts by mass allocation. The decision was based on the fact that LVL as the final product contained more than 90 percent of the mass leaving the system and because the specific gravities of both LVL and associated coproducts were similar. The earlier CORRIM study applied mass allocation, whereas in this study, economic allocation was performed in addition to mass allocation because the wood product PCR suggests using economic allocation for a multioutput process when the difference in revenues is more than 10 percent (FPInnovations 2015). The results of the analysis using economic allocation are provided.

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Functional unit

In accordance with the PCR (FPInnovations 2015), the declared unit for LVL was 1 cubic meter (1 m^3). A declared unit was used in instances where the function and the reference scenario for the whole life cycle of a wood building product cannot be stated (ISO 2007, FPInnovations 2015). For conversion of units from the US LVL industry measure, 1 ft^3 of LVL equals 0.02832 m^3 with a final product ovendried moisture content of 6 percent. All input and output data were allocated to the declared unit of product based on the mass of products and coproducts in accordance with ISO 14044 (ISO 2006b). As the analysis does not take the declared unit to the stage of being an installed building product, no service life was assigned.

System boundaries

The system boundary begins with regeneration in the forest and ends with LVL at the mill gate (Fig. 1). The system boundary included forest resources, transportation of roundwood to the primary breakdown facility, dry veneer production, dry veneer transportation to the LVL facility if needed, phenol-formaldehyde (PF) resin production, and LVL production. Three unit processes in LVL manufacturing included lay-up, hot pressing, and sawing and trimming. Packaging of LVL was also considered in the system boundary. Resources used for the cradle-to-gate production of energy and electricity consumed on-site were included within the cumulative system boundary. In addition, ancillary material consumption data, such as motor oil, paint, and hydraulic fluid, were included in the analysis. Off-site emissions that were accounted for include those from grid electricity production, transportation of feedstock and the resin, and off-site fuel production.

System investigated

The cradle-to-gate LCA of LVL manufacturing included three major life stages: forestry operations, dry veneer production, and LVL production. The PF resin used in LVL production as part of the resin system was included in the analyses and considered as an upstream process in LVL production.

Forest operations.—Forest resource management (i.e., forest operations) include the production of the logs used in the production of LVL. Their life-cycle activities include the establishment, growth, and harvest of trees. Forestry operations vary regionally (Johnson et al. 2005) but typically include some combination of growing seedlings, regeneration, site preparation, planting (where applicable), thinning, fertilization (where applicable), and final harvest. Harvesting includes felling, skidding, processing, and

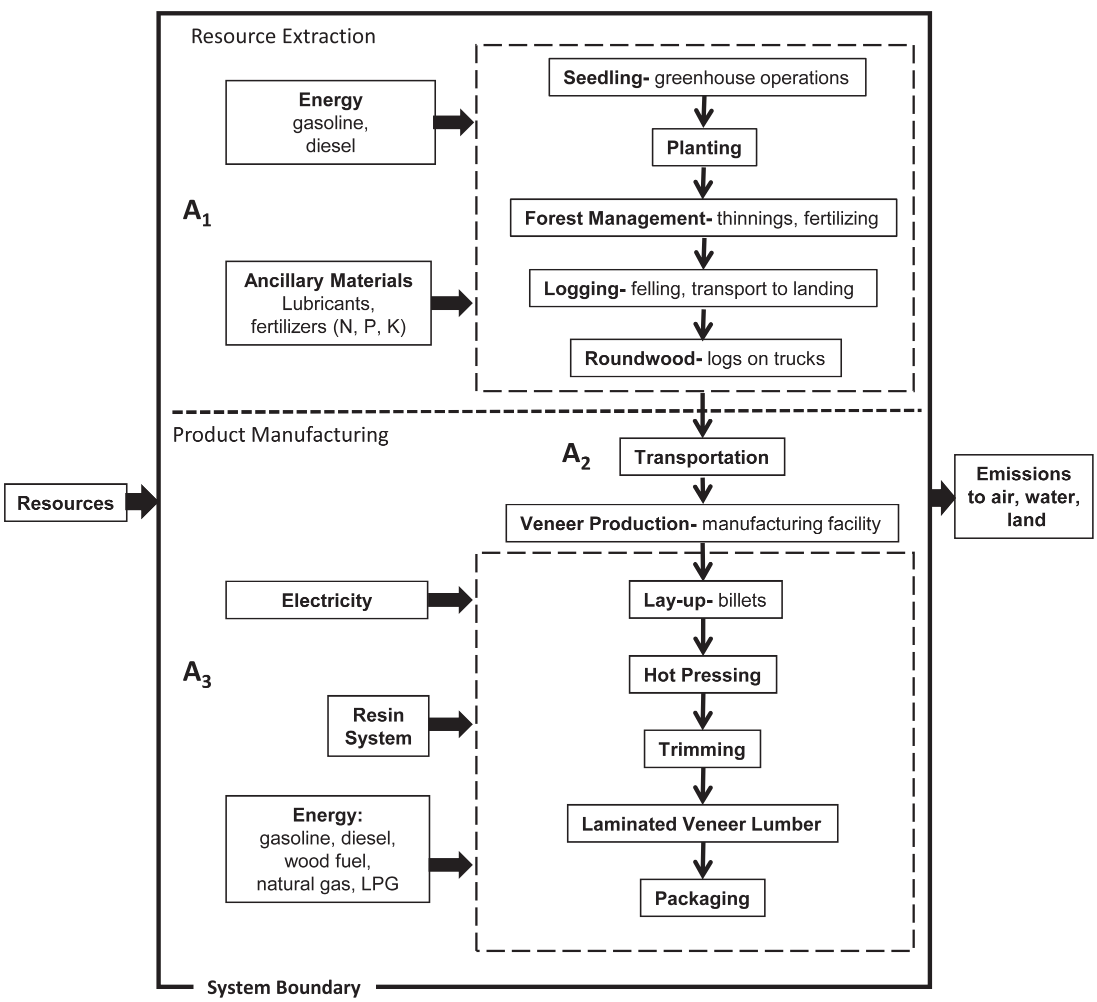

Figure 1.—Cradle-to-gate system boundary and process flow for production of laminated veneer lumber.

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loading for both commercial thinning and final harvest operations. The primary output product is a log destined for softwood veneer. The coproduct, nonmerchantable (logging) slash, is generally left at a landing. Slash disposal was not modeled, as it was assumed to decay in situ. Forest operations modeled as inputs to dry veneer and LVL production were based on forest resource LCI data inputs from the PNW and SE softwood forests (Johnson et al. 2005; Puettmann et al. 2013a, 2013b).

Veneer production.—Dry softwood veneer plies were used in LVL production. The moisture content of the dry veneer ranges from 3 to 6 percent (ovendry basis). In the PNW region, the dry veneer made into LVL comes from logs of many softwood species representing a mix of Douglas-fir (*Pseudotsuga menziesii*), white fir (*Abies concolor*), western hemlock (*Tsuga heterophylla*), lodgepole pine (*Pinus contorta*), and western larch (*Larix occidentalis*). In the SE region, dry veneer comes from the softwood species representing a mix of longleaf pine (*Pinus palustris*), shortleaf pine (*Pinus echinata*), slash pine (*Pinus elliotti*), and loblolly pine (*Pinus taeda* L.) along with some hardwood, mostly from yellow poplar (*Liriodendron tulipfera*) and a little from red maple (*Acer rubrum*). In this study, the dry veneer data provided by M. Puettmann (personal communication, April 24, 2015) on softwood plywood production were adopted.

PF resin.—The LCI for the production of PF resin covered its life cycle from extraction of in-ground resources through the production and delivery of input chemicals and fuels through to the manufacturing of a resin as shipped to the customer (Wilson 2010). The PF resin survey data were from 13 plants in the United States that represented 62 percent of total production for the year 2005 (Wilson 2009). The inputs to produce 1 kg of neat PF resin consist of the two primary chemicals, 0.244 kg of phenol and 0.209 kg of methanol, and a lesser amount of sodium hydroxide (0.061 kg) and 0.349 kg of water. Electricity is used for running fans and pumps and for operating emissions control equipment. Natural gas is used for boiler fuel and emission control equipment, and propane fuel is used in forklifts.

LVL production.—Three main unit processes were considered in LVL manufacturing, including lay-up, hot pressing, and trimming and sawing. For the lay-up unit process, the lay-up lines are used to arrange pieces of the proper grades of dry veneer into the assembly process, resin is applied, and the veneers are assembled into a mat before pressing (Baldwin 1995, Wilson and Dancer 2005). First, a veneer feeder assembly places veneer pieces into the lay-up sequence. Even though LVL can vary in thickness and width, it is most commonly produced in the dimensions of 4.45 cm (1¾ in.) thick and 122 cm (4 ft) wide into lengths from 2.44 to 18.3 m (8 to 60 ft). After pieces of veneer are arranged onto the lay-up conveyor, resin is applied to each piece of veneer, except for the top veneer layer in the LVL billet. Afterward, the LVL mat is assembled layer by layer. Inputs include dry veneer and resins, and outputs include LVL billet, lay-up scrap, and small amounts of volatile organic compounds (VOCs) and hazardous air pollutants (HAPs). Although small amount of fugitive VOCs and HAPs are emitted, they are accounted for within the hot-pressing unit process.

For the hot-pressing unit process, heat and pressure applied during hydraulically pressing cure the resin, thus binding the veneer layers together. Inputs include uncured LVL billets, while outputs include cured LVL billets along with emissions of particulate matter (PM), $PM_{2.5}$, VOCs, and HAPs released from heating of the wood and curing of the resins. Cold pressing can also occur at some production facilities when wider LVL billet beams are produced.

For the trimming and sawing unit process, the LVL billet is sawn to the desired dimensions. The wood residue generated during trimming and sawing is collected pneumatically into a wood waste collection system (i.e., baghouses). Once sawn, a protective and cosmetic sealant is sometimes applied to the LVL. Inputs include LVL billets and sealant, and output includes finished LVL, (used) tested LVL, and wood residues along emissions of PM, $PM_{2.5}$, and PM_{10} from collecting wood residues and VOCs and HAPs from the application and curing of sealant.

Inventory approach

The relevant primary quantitative data to develop gate-to-gate inventory, including input and output flows associated with the unit processes included in the system boundaries of LVL production, were collected through surveys. The surveyed plants provided detailed annual production data on their facilities for the year 2012. This survey tracked raw material and energy inputs, product and by-product outputs, and pertinent emissions to water and air as well as solid waste generation. Secondary data, such as pre–mill gate processes (e.g., forestry operations, dry veneer production, and electricity production), were retrieved from peer-reviewed literature and public databases.

There were two major energy sources used at the LVL plants: electricity and natural gas. The electrical grid composition for the PNW and SE regions of the United States was adopted from the US LCI database (NREL 2012). Natural gas (31.8%) and coal (30.2%) power made up most of the PNW (WECC) grid, while coal (56.4%) and nuclear (25.2%) made up most of the SE (SERC) grid. Another major on-site energy source used was natural gas. Burning natural gas generated steam that was then used in the hot-pressing unit process.

For the cradle-to-gate LCA analysis, the gate-to-gate LVL LCI data developed using the survey data were linked to available forest resources (Johnson et al. 2005; Puettmann et al. 2013a, 2013b), dry veneer production LCI data (Kaestner 2015; M. Puettmann, personal communication, April 24, 2015), and finished LVL packaging (Puettmann et al. 2013a, 2013b) along with any required transportation to construct the cradle-to-gate LCI. Complete details of this study for LCI development for LVL production and the CORRIM project can be found in Bergman and Alanya-Rosenbaum (2017a, 2017b).

Cutoff rules

According to the PCR (FPInnovations 2015), if the mass–energy of a flow is less than 1 percent of the cumulative mass–energy of the model flow, it may be excluded, provided that its environmental relevance is minor. This analysis included all energy and mass flows for primary data.

In the primary surveys, manufacturers were asked to report total HAPs specific to their wood products manufacturing process regardless of whether they were less than the 1 percent cutoff. These are methanol, acetaldehyde, formaldehyde, propionaldehyde (propanal), acrolein, and

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phenol. If applicable to the wood product, HAPs are reported in the LCI Data section of Bergman and Alanya-Rosenbaum (2017a, 2017b). Under Title III of the Clean Air Act Amendments of 1990, the US EPA has designated HAPs that wood products facilities are required to report as surrogates for all HAPs. All HAPs are included in the LCI; no cutoff rules apply.

Data quality requirements

The present study collected data from representative LVL manufacturers in the PNW and the SE that use average technology for their regions. The dry veneer produced at the product manufacturing facilities mills in the two regions of the United States is the raw wood input to LVL production.

Total US LVL production for 2012 was 1.31 million m^3. The United States has eight companies with 15 operating production facilities, with seven in the PNW region and eight in the SE region. Of the 15 plants, six facilities participated in the study. Two US LVL plants representing 8.5 percent of 2012 US production (0.111 million m^3) for the PNW region and four US LVL plants representing 26.4 percent of 2012 US production (0.344 million m^3) for the SE region participated in the study by providing primary data for each region (APA—The Engineered Wood Association 2014). Although the number of plants surveyed may be small compared with a ''typical'' mail survey, the level of detail and amount of primary mill data were very high. Each facility contributed a substantial amount of time completing the questionnaire, ranging from 20 to 28 hours, with an average of 24 hours, including follow-up questions. In addition, to aid in data quality, the authors conducted a site visit after all the survey data were collected and analyzed. The PNW and the SE are the primary regions for producing structural wood products such as LVL. The surveyed plants provided detailed annual production data on their facilities, including on-site energy consumption, electrical usage, veneer volumes, and LVL production for 2012. Wilson and Dancer (2005) performed a 2000 US LVL LCI study that covered 34 percent (0.187 million m^3) and 52 percent (0.221 million m^3) of production for the PNW and the SE, respectively. The production of surveyed facilities for 2012 showed a decrease of 40 percent from 2000 for the PNW and an increase of 56 percent for the SE. In addition, unlike the earlier 2000 study, 2012 LVL production data were not available by region. Therefore, total LVL production data by region could not be quantified for 2012.

To ensure data of the highest quality, data control measures were taken. Quantitative mass balances were performed to verify data quality. First, mass balances at individual facilities were conducted where the data were found to be consistent for the surveyed mills. Second, overall wood mass in and total wood mass out for both regions were calculated, and the difference was less than 2 percent. A difference less than 10 percent is considered good for wood product production. In addition, the primary data obtained from the surveys were weight averaged. The weighted coefficient of variation representing the variability in the collected process data was calculated and presented. Additionally, a sensitivity analysis investigating the energy inputs into LVL production was performed to investigate the robustness of the impact assessment results.

Assumptions and limitations

The data collection, analysis, and assumptions followed the protocol defined by CORRIM in ''Research Guidelines for Life-Cycle Inventories'' (2014). To conform to ISO 14040 (ISO 2006c), additional considerations are listed below:

1. Although small in quantity relative to the wood mass, impacts from production of the resin system were included in the analysis.
2. The authors did not collect 2012 primary forest resource data but used secondary data from earlier LCA studies to develop the cradle-to-gate analysis. It is expected that forest resource data will be updated in the near future. As mentioned previously, to develop new EPDs, new underlying LCA data must be continually generated per the North American wood product PCR (FPInnovations 2015).
3. For the secondary data for forest resource incorporated into the analysis, data included growing seedlings, planting, thinning, fertilization (where applicable), and final harvest.
4. For regional forest harvesting, a single estimate of the average volume harvested per unit area was developed by weighting three combinations of management intensity (low, medium, and high intensity) and site productivity based on the relative percentage of the land base they occupy. Puettmann et al. (2013a, 2013b) list specific inputs, input assumptions, variations in harvest equipment, and fuel consumptions for the three management intensities for the two regions.
5. Harvesting cycles averaged 27 and 45 years for the SE and PNW regions, respectively.
6. Land use impacts, including biodiversity, were not incorporated into the present study. The forests were considered to be replanted as forests and eventually returned to their previous state.
7. Forest carbon increases and decreases were not tracked but considered that the harvested trees were being sustainably managed through the ASTM standards D7612-10 and D7480-08 (ASTM International 2010, 2014b).
8. Temporal dimensions of greenhouse gas (GHG) emissions were not included because the study focused on the cradle-to-gate production, which occurs within a relatively short time frame, versus cradle-to-grave production, where long-term GHG emissions and carbon sinks have a greater influence on the global warming (GW) impact category (Bergman 2012).
9. All flow analyses of wood and bark in the process were determined on an ovendry weight basis using a weighted production density of 543 and 563 kg/m^3 for the PNW and the SE, respectively.
10. The water consumption for two SE plants were combined with dry veneer production. Veneer production consumed 285 liters/m^3 LVL, with the rest, 2 liters/m^3, allocated to SE LVL production (Kaestner 2015, Puettmann et al. 2016a).
11. Biogenic CO_2 emissions were tracked and reported, but the TRACI 2.1 impact method (Bare 2011) does not count the contribution of wood-derived CO_2 emissions from burning wood fuel in the boiler toward the GW impact estimate.

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Table 1.—Gate-to-gate material flow analysis of 1 m^3 of laminated veneer lumber (LVL) manufacturing in the Southeast (SE) and Pacific Northwest (PNW) regions.

		Value	
	Unit	SE	PNW
Products[a]			
Laminated veneer lumber	m^3	1.00	1.00
Sawdust, sold	kg	43.99	52.74
Sawdust, wood fuel	kg	6.31	0.00
Panel trim, sold	kg	5.56	3.41
Lay-up scrap	kg	0.00	2.94
Tested LVL, used	kg	0.00	5.88
Other, not specified	kg	16.00	0.00
Resources			
Water, well, in ground	liters	2.43	1.74
Materials			
Wood feedstock, produced dry veneer[a]	kg	254.25	0.00
Wood feedstock, purchased dry veneer[a]	kg	358.08	584.95
Phenol-formaldehyde resin	kg	22.68	17.75
Sodium hydroxide	kg	0.00	3.19
Catalyst	kg	0.00	0.25
Melamine	kg	0.00	1.57
Ancillary material			
Hydraulic fluid	kg	0.0138	0.0138
Greases	kg	0.0017	0.0017
Motor oil	kg	0.0340	0.0340
Waxes (sealant)	liters	0.6195	0.3022
Paint	liters	0.1787	0.0029

[a] Ovendry basis.

12. Carbon content for wood products is assumed to be 50 percent by mass of ovendried wood.
13. As mentioned previously, the regional LVL production for year 2012 was not available; therefore, quantitative regional representativeness was not provided.

Impact category method

The LCIA was performed using the TRACI 2.1 method (Bare 2011). TRACI is a midpoint impact assessment method developed by the US EPA specifically for the United States. Five impact categories were examined, including GW (kg CO_2 eq), acidification (kg SO_2 eq), eutrophication (kg N eq), ozone depletion (kg chlorofluorocarbons-11 eq), and photochemical smog (kg O_3 eq). These five impact categories are reported consistent with the requirement of the wood products PCR (FPInnovations 2015). In this study, environmental burdens were assigned to the LVL and the coproducts (i.e., sawdust) both by mass and economic value in order to investigate the effect of allocation method on the results.

Table 2.—Gate-to-gate weighted-average on-site energy inputs to produce 1 m^3 of laminated veneer lumber.

Energy inputs	Southeast			Pacific Northwest		
	Quantity	Unit	CoVw (%)[a]	Quantity	Unit	CoVw (%)
Electricity	98.2	kWh	55	77.4	kWh	61
Natural gas	19.3	m^3	53	12.8	m^3	11
Diesel	0.74	liters	69	0.35	liters	37
Propane	0.78	liters	10	0.48	liters	52
Gasoline	0.06	liters	244	0	liters	

[a] CoVw = production-weighted coefficient of variation.

Table 3.—Direct outputs resulting from production of 1 m^3 of laminated veneer lumber, gate to gate.[a]

	Unit	Southeast	Pacific Northwest
Emissions to air			
Acetaldehyde	kg	0.0028	0.0028
Acrolein	kg	0.0000	0.0000
Carbon monoxide	kg	0.0460	0.0102
Formaldehyde	kg	0.0029	0.0045
Hexane	kg	0.0000	0.0002
Lead	kg	0.0000	0.0000
Methanol	kg	0.0620	0.1178
Nitrogen oxides	kg	0.0012	0.0130
$PM_{2.5}$	kg	0.0890	0.0502
PM_{10}	kg	0.0890	0.1004
Particulates, unspecified	kg	0.0860	0.1181
Phenol	kg	0.0000	0.0000
Propionaldehyde	kg	0.0038	0.0038
Sulfur dioxide	kg	0.0003	0.0000
VOC	kg	0.3337	0.4641
Solid waste			
Waste to inert landfill	kg	4.66	0.86
Waste to recycling	kg	3.08	0.40

[a] PM = particulate matter; VOC = volatile organic compounds.

Sensitivity analysis

A sensitivity analysis was performed to determine how sensitive the results are to certain changes in parameters (i.e., on-site natural gas and electricity consumption) at the LVL plant. Analysis was completed in line with ISO 14040 standards (ISO 2006c). The effect of variation in the consumption of natural gas and electricity on cumulative primary energy consumption (CPEC) and GHG emissions was investigated.

Critical review

An internal review of this cradle-to-gate LVL LCA study, including the associated SimaPro model, was conducted by Dr. Maureen Puettmann, WoodLife Environmental Consultants. The purpose of the internal review was to check for errors and for conformance with the PCR prior to external review.

Results

The LCA analyses were performed based on the updated LCI data where regional industry data for year 2012 LVL

Table 4.—Weighted-average delivery distance (one way) by mode for materials to laminated veneer lumber plant.

	Delivery distance (km)	
	Southeast	Pacific Northwest
Purchased dry veneer, by truck	392	108
Purchased dry veneer, by rail	216	—
Phenol-formaldehyde resin, by truck	271	79
Wood fuel, by truck	0.1	—
Log with bark to veneer production, by truck	100	104

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Table 5.—Cumulative primary energy consumption per 1 m^3 of cradle-to-gate laminated veneer lumber (LVL) (mass allocation).

Fuel	Southeast				Pacific Northwest			
	%	Forestry operations	Veneer production	LVL production	%	Forestry operations	Veneer production	LVL production
Renewable fuel use								
Wood fuel	36.2	0.00E+00	3.58E+03	3.15E+01	52.5	0.00E+00	4.68E+03	2.50E+01
Nonrenewable fuel use								
Natural gas	28.4	5.45E+01	1.45E+03	1.32E+03	21.1	9.31E+00	7.10E+02	1.17E+03
Coal	18.2	7.25E+00	1.06E+03	7.49E+02	11.9	4.95E+00	6.77E+02	3.81E+02
Crude oil	9.6	1.91E+02	2.92E+02	4.74E+02	8.8	1.47E+02	3.43E+02	2.96E+02
Uranium	7.4	2.41E+00	4.34E+02	3.06E+02	3.5	1.69E+00	2.07E+02	1.09E+02
Other renewable energy sources								
Hydropower	0.2	4.23E−03	9.09E+00	7.68E+00	1.8	3.65E−03	1.07E+02	5.61E+01
Other	0.0	0.00E+00	1.10E−01	8.03E−02	0.4	0.00E+00	2.20E+01	1.14E+01
Total (%)	100	2.6	68.5	29.0	100	1.8	75.3	22.9

production in the United States were analyzed using the weighted-average approach. Primary data were collected through a survey questionnaire mailed to LVL plants in the United States for year 2012, where LVL production in the United States was about 1.31 million m^3.

LCI analysis

Material inputs to develop gate-to-gate LVL LCIs for the SE and PNW regions are provided in Table 1. To evaluate data quality, a weighted-average mass balance of the LVL plants was performed. The data consistency was high based on the weighted production coefficient of variation (CoVw) values calculated for system inputs and outputs. For the final product, LVL, the data showed good consistency between facilities, with a CoVw of 4.0 and 2.9 percent for the SE and the PNW, respectively. In addition, the CoVw for total feedstock was 6.5 percent (SE) and 4.1 percent (PNW).

Weighted-average energy inputs consumed on-site at the LVL manufacturing sites in SE and PNW plants are presented in Table 2. Electricity and natural gas were the primary energy inputs, where natural gas was used to generate heat. The production-weighted CoVw showed large variation for both regions except for propane consumption for the SE and natural gas consumption for the PNW (10% and 11%, respectively). At SE plants, gasoline consumption showed the largest variation.

Air emissions from the LVL plant were derived from the surveyed mills along with pertinent emissions data categorized by the US EPA (2002). When available, surveyed air emission data as primary data were selected over secondary data (Table 3). Waste generated was incorporated in the analysis as well.

Transport of materials to the LVL plant was accounted for in the analysis. The weighted-average transport distance for feedstock along with the resin to the LVL plants based on the survey results is provided in Table 4.

Cumulative energy consumption

Table 5 presents the cradle-to-gate CPEC per 1 m^3 of LVL in the SE and PNW regions. The major energy source

Table 6.—Environmental performance of 1 m^3 of laminated veneer lumber (LVL), cradle to gate, Southeast (mass allocation).

	Unit[a]	Total	Forestry operations	Veneer production	LVL production
Impact category					
Global warming	kg CO_2 eq	3.39E+02	1.61E+01	1.84E+02	1.40E+02
Acidification	Kg SO_2 eq	3.26E+00	2.17E−01	1.76E+00	1.28E+00
Eutrophication	kg N eq	1.22E−01	4.27E−02	3.83E−02	4.11E−02
Ozone depletion	kg CFC-11 eq	1.69E−07	1.46E−09	1.14E−08	1.56E−07
Smog	kg O_3 eq	3.56E+01	6.07E+00	1.94E+01	1.00E+01
Primary energy consumption					
Nonrenewable fossil	MJ	5.60E+03	2.52E+02	2.80E+03	2.55E+03
Nonrenewable nuclear	MJ	7.43E+02	2.41E+00	4.34E+02	3.06E+02
Renewable (solar, wind, hydroelectric, and geothermal)	MJ	1.70E+01	4.23E−03	9.20E+00	7.76E+00
Renewable, biomass	MJ	3.61E+03	0.00E+00	3.58E+03	3.15E+01
Total primary energy consumption	MJ	9.98E+03	2.55E+02	6.83E+03	2.89E+03
Material resources consumption (nonfuel resources)					
Nonrenewable materials	kg	1.75E+00	0.00E+00	1.72E+00	2.66E−02
Renewable materials	kg	8.84E+02	0.00E+00	8.79E+02	4.87E+00
Freshwater	liters	1.33E+03	5.94E−02	9.01E+02	4.26E+02
Waste generated					
Solid waste	kg	2.17E+01	0.00E+00	1.48E+01	6.86E+00

[a] CFC = chlorofluorocarbons.

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Table 7.—Environmental performance of 1 m^3 laminated veneer lumber (LVL), cradle to gate, Pacific Northwest (mass allocation).

	Unit[a]	Total	Forestry operations	Veneer production	LVL production
Impact category					
Global warming	kg CO_2 eq	2.18E+02	1.08E+01	1.16E+02	9.12E+01
Acidification	kg SO_2 eq	2.29E+00	1.49E−01	1.26E+00	8.75E−01
Eutrophication	kg Ne	7.70E−02	1.03E−02	3.78E−02	2.89E−02
Ozone depletion	kg CFC-11 eq	4.75E−07	4.87E−10	8.67E−09	4.66E−07
Smog	kg O_3 eq	3.12E+01	4.67E+00	1.98E+01	6.74E+00
Primary energy consumption					
Nonrenewable fossil	MJ	3.74E+03	1.61E+02	1.73E+03	1.85E+03
Nonrenewable nuclear	MJ	3.18E+02	1.69E+00	2.07E+02	1.09E+02
Renewable (solar, wind, hydroelectric, and geothermal)	MJ	1.96E+02	3.65E−03	1.29E+02	6.75E+01
Renewable, biomass	MJ	4.71E+03	0.00E+00	4.68E+03	2.50E+01
Total primary energy consumption	MJ	8.97E+03	1.63E+02	6.75E+03	2.05E+03
Material resource consumption (nonfuel resources)					
Nonrenewable materials	kg	5.11E+00	0.00E+00	5.11E+00	5.47E−05
Renewable materials	kg	8.62E+02	0.00E+00	8.57E+02	4.87E+00
Freshwater	L	1.22E+03	1.03E+01	8.76E+02	3.36E+02
Waste generated					
Solid waste	kg	9.15E+00	0.00E+00	8.02E+00	1.13E−01

[a] CFC = chlorofluorocarbons.

used was wood fuel, about 36 and 53 percent for the SE and the PNW, respectively, resulting primarily from veneer production, which was used to generate thermal energy for log conditioning and drying and pressing veneers. Thus, 99 percent of the biogenic CO_2 was released during veneer production (280 and 394 kg per 1 m^3 of LVL were produced in the SE and the PNW, respectively). For LVL production, energy consumption was dominated by fossil fuels, that is, natural gas and coal. Natural gas was used primarily for thermal energy generation for hot pressing the LVL billets and some for fueling thermal oxidizers for emission controls. Coal consumption in the SE (18%) and PNW (12%) resulted from coal-based electricity generation. Other resources used for electricity generation included hydroelectric, wind, solar, and geothermal energy resources. Forestry operations consumed relatively low energy, which was exclusively fossil fuels: 2.6 and 1.8 percent of the CPEC for the SE and PNW, respectively.

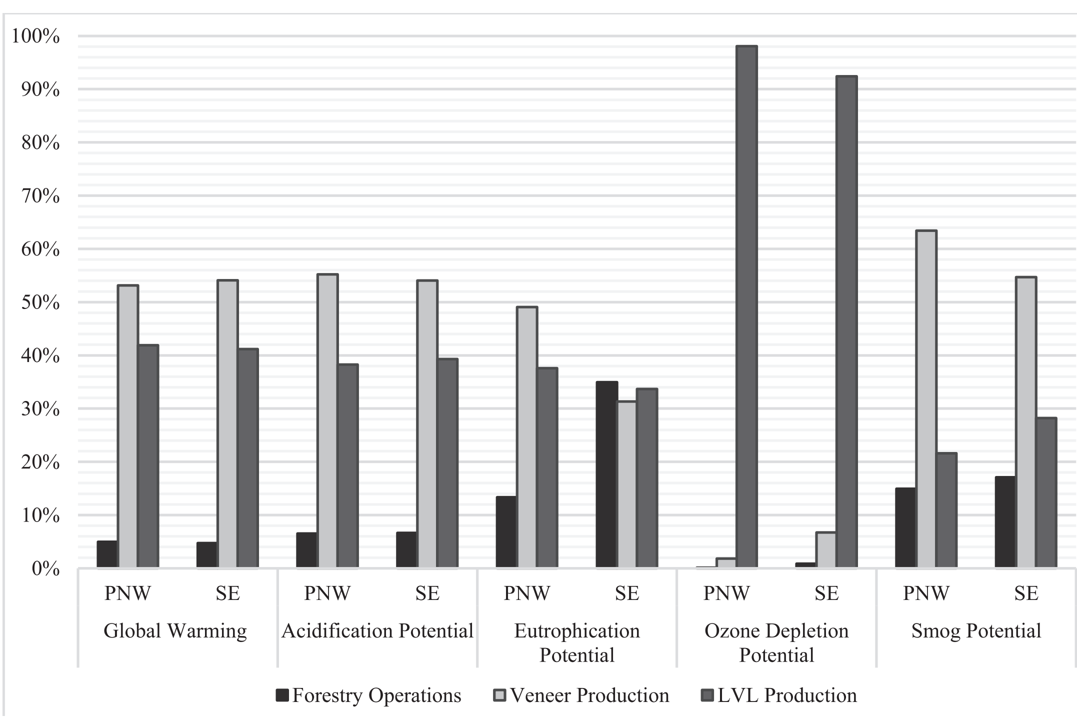

Figure 2.—Contribution of the life-cycle stages of laminated veneer lumber (LVL) production to the resulting environmental impact in the Pacific Northwest (PNW) and Southeast (SE) regions of the United States (mass allocation).

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Table 8.—Carbon balance per 1 m^3 of laminated veneer lumber.

Carbon source	kg CO_2 eq	
	Southeast	Pacific Northwest
Released forestry operations	16.1	10.8
Released manufacturing	323	207
CO_2 equivalent stored in product	995	959

Life-cycle impact assessment

In this study, five midpoint impact categories were investigated. Environmental performance results for five impact categories along with energy consumption from nonrenewables; renewables; wind, hydroelectric, solar, geothermal, and nuclear fuels; renewable and nonrenewable resource use; and solid waste generated are presented in Tables 6 and 7 for the SE and the PNW, respectively. The results showed that the total primary energy consumption in the SE region for all three life-cycle stages is 9.98 GJ/m^3, where it was 8.97 GJ/m^3 in the PNW region. In both the SE and the PNW, the veneer production life-cycle stage consumed the most primary energy at 6.83 GJ/m^3 (68.5%) and 6.75 GJ/m^3 (75.3%), respectively.

The contribution of major substances to the overall impact for the five impact categories considered are provided in Figure 2. Considering the GW impact category in terms of the contribution of life-cycle stages, the greatest contributor at both regions was veneer production, above 52 percent, followed by LVL manufacturing. The veneer production stage process dominates the impact at both regions, with about more than 50 percent contribution, for all impact categories except for ozone depletion and eutrophication. Of the two, the ozone depletion category stands out because it was dominated by the LVL stage. This was due mainly to the resin consumption occurring at the lay-up process. Electricity consumption followed by natural gas use had notable contributions to GW at the LVL manufacturing stage, where electricity has contributions of 42 and 45 percent to overall GW for the PNW and SE, respectively. Overall, the contribution of forestry operations to the resulting impacts was minor.

The approach for biogenic carbon accounting was adopted from the Norwegian Solid Wood Product PCR (Aasestad 2008) and the North American PCR (FPInnovations 2015) to ensure comparability and consistency. The North American PCR approach was followed for GW impact reporting; therefore, the default TRACI impact assessment method was used. This default method does not count the CO_2 emissions released during the combustion of woody biomass during production. Other emissions associated with wood combustion, such as fossil CO_2, methane, or nitrogen oxides, do contribute to and are included in the GW impact category. Using this method, total (fossil and biogenic) GHG emissions released were calculated as 323 and 207 kg for the SE and PNW, respectively, in the production of 1 m^3 of LVL (Table 8). That same 1 m^3 of LVL stores 995 and 959 kg CO_2 eq for the SE and PNW, respectively.

Scenario analysis

The influence of using the mass and value allocation on the final product, LVL, and its associated coproducts on the impact assessment results were analyzed (Tables 9 and 10). The cradle-to-gate impact assessment results for the

Table 9.—Environmental impact assessment results for mass and value allocation for the Southeast region.[a]

Impact category	Unit	Allocation method	Forestry operations (%)	Veneer production (%)	LVL production (%)
Global warming	kg CO_2 eq	Mass allocation	4.7	54.1	41.2
		Value allocation	4.6	50.0	45.4
Acidification	kg SO_2 eq	Mass allocation	6.6	54.1	39.3
		Value allocation	6.5	49.9	43.5
Eutrophication	kg N eq	Mass allocation	35.0	31.3	33.7
		Value allocation	34.5	28.1	37.4
Ozone depletion	kg CFC-11 eq	Mass allocation	0.9	6.7	92.4
		Value allocation	0.8	1.6	97.6
Smog	kg O_3 eq	Mass allocation	17.1	54.7	28.2
		Value allocation	17.1	51.2	31.8

[a] LVL = laminated veneer lumber; CFC = chlorofluorocarbons.

Table 10.—Environmental impact assessment results for mass and value allocation for the Pacific Northwest region.[a]

Impact category	Unit	Allocation method	Forestry operations (%)	Veneer production (%)	LVL production (%)
Global warming	kg CO_2 eq	Mass allocation	5.0	53.2	41.9
		Value allocation	4.9	49.0	46.1
Acidification	kg SO_2 eq	Mass allocation	6.5	55.2	38.3
		Value allocation	6.5	51.1	42.5
Eutrophication	kg N eq	Mass allocation	13.3	49.1	37.6
		Value allocation	13.3	45.0	41.8
Ozone depletion	kg CFC-11 eq	Mass allocation	0.1	1.8	98.1
		Value allocation	0.1	0.4	99.5
Smog	kg O_3 eq	Mass allocation	15.0	63.4	21.6
		Value allocation	15.1	60.5	24.4

[a] LVL = laminated veneer lumber; CFC = chlorofluorocarbons.

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categories taken into consideration showed only a slight difference (1% to 2%) except for the ozone depletion impact category (6% and 10% for the SE and PNW, respectively), which is because of the increased contribution of the LVL production stage. Value allocation resulted in a 12 to 13 percent increase in the impact resulting from the LVL stage in all impact categories. This was owing to the environmental burdens shifted toward the production of LVL, where the economic value of the coproducts was minor. The difference in impact resulting from the veneer production stage ranged between 6 and 9 percent in all impact categories except ozone depletion. The ozone depletion impact category of the veneer production stage was about four times lower for value allocation compared with mass allocation in both regions. However, because the impact from ozone depletion was far higher for the LVL production stage, the difference between value and mass allocation for the overall ozone depletion impact was not major. Regardless, most of the ozone depletion impact at the veneer production stage was assigned to the wood boiler used in veneer drying. The fuel used in the wood boiler was a mixture of the coproducts coming from a downstream process at plywood production. The lower ozone depletion for economic allocation was a result of lower emissions allocated to coproducts owing to their low economic value. In addition, the difference in CPEC between the mass and value allocation was not significant at below 3 percent.

Comparison

To validate LCA studies, comparisons were performed. This study compared the energy inputs from the current 2012 study with the earlier CORRIM Phase I study to show how the CPEC for LVL was affected. The on-site, industry-average energy inputs reported in 2012 were substantially higher than for Phase I (Wilson and Dancer 2005; Puettmann et al. 2010, 2013a, 2013b). In particular, for the SE, electricity and natural gas consumption drove the total impact from energy with changes of 41 and 76 percent, respectively (Table 11). As expected from the higher CPEC value found earlier, the on-site energy inputs were substantially higher than for Phase I for the PNW as well (Wilson and Dancer 2005; Puettmann et al. 2013a, 2013b). In particular, electricity and natural gas consumption drove the total impact from energy with changes of 30 and 234 percent, respectively (Table 12). Therefore, a sensitivity analysis that investigated the energy inputs into LVL production was completed to see their overall impact. However, the apparent statistical differences between the older and current studies could not be adequately addressed because no statistical description of the data from the earlier study was available. The earlier CORRIM study did not perform sensitivity analysis. However, there was sufficient reason to attempt to quantify the energy impacts associated with LVL production.

Table 11.—Production weighted-average Southeast (SE) on-site energy inputs for manufacturing 1.0 m^3 of laminated veneer lumber.

	Quantity			
Energy inputs	SE Phase I	SE 2012	Unit	% change
Electricity	69.6	98.2	kWh	41
Natural gas	10.9	19.3	m^3	76
Diesel	0.370	0.740	liters	100
Propane	0.480	0.785	liters	63

Table 12.—Production weighted-average Pacific Northwest (PNW) on-site energy inputs for manufacturing 1.0 m^3 of laminated veneer lumber.

	Quantity			
Energy inputs	PNW Phase I	PNW 2012	Unit	% change
Electricity	59.5	77.4	kWh	30
Natural gas	3.83	12.8	m^3	234
Diesel	0.169	0.351	Liters	108
Propane	0.250	0.477	Liters	91

Sensitivity analysis

A sensitivity analysis was performed in accordance with the ISO 14040 standard to model the cradle-to-gate effects of varying on-site natural gas consumption and electricity consumption for LVL production. The effect of a 20 percent variation in the consumption of natural gas and electricity at the LVL plant on the CPEC and GW impact was investigated. Sensitivity analysis revealed that neither natural gas nor electrical consumption on-site had a substantial effect on cradle-to-gate CPEC and GW impact. This is due to fact that the dry veneer production had a relatively large effect in comparison with the environmental indicators associated with energy consumption, as shown in Table 5.

Conclusions

Wood products typically consume more renewable than nonrenewable energy sources, as shown by this present study. This study conducted the cradle-to-gate LCIA for LVL production for the SE and PNW regions of the United States. The inventory analysis showed that woody biomass, by far the largest renewable energy source, represented 36.2 and 52.5 percent of the CPEC for the SE and PNW, respectively. This was strongly driven by the veneer production, where wood boilers were used for thermal energy generation, as they are for most wood product production stages. Energy use in LVL production was dominated by fossil fuels, primarily natural gas and coal, because less woody biomass was available for thermal energy and by resin production. Resin, although a small portion of the final product, had a far greater influence on most impact categories on a mass basis than wood itself.

As expected, the two wood product production life-cycle stages consumed the most energy when evaluated by a cradle-to-gate analysis. LCIA results revealed that the veneer production stage was the greatest contributor to most impact categories investigated. However, the ozone depletion category was dominated by the LVL stage due to the resin used in LVL manufacturing. Electricity consumption, followed by natural gas use, has a notable contribution to the GW category at the LVL manufacturing stage, where electricity has contributions of 42 and 45 percent to overall GW in the PNW and SE, respectively. The contribution of forest operations to energy consumption and the resulting environmental impact were minor relative to manufacturing emissions (veneer and LVL).

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In this study, cradle-to-gate CPEC of LVL production for the United States was substantially higher compared with earlier CORRIM studies. Yet the authors can only speculate regarding the apparent differences because of the lack of statistical analysis of the data from other, earlier studies. The scenario analysis conducted indicated that LVL production itself was a minor contributor to the overall process because veneer production largely outweighs LVL production in terms of energy inputs. As for energy inputs for LVL production itself, one possible explanation is the higher use of emission control devices, including baghouses and regenerative catalytic oxidizers (or thermal oxidizers) becoming more prevalent because of increased regulatory controls in the United States since the 2000s, when the original survey data were collected. Because thermal oxidizers are more commonly used today in the manufacturing of wood products to eliminate VOC emissions, it would have a significant effect on the results in other wood product systems as well. In support of this conclusion, the updated oriented strandboard study also reported increased use of regenerative thermal oxidizers, which caused high natural gas consumption (Puettmann et al. 2016b). Plywood studies also reported installation of regenerative thermal oxidizers and electrostatic precipitators at the surveyed mills between 2000 and 2012 (Puettmann et al. 2016a). Therefore, the resultant higher CPEC values for 2012 than for 2000 ought to be considered as an environmental trade-off to lower emissions such as VOCs (or HAPs).

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Literature Cited

Aasestad, K. 2008. The Norwegian Emission Inventory 2008. Documentation of methodologies for estimating emissions of greenhouse gases and long-range transboundary air pollutants. Statistisk sentralbyrå. Reports 2008/48. 252 pp.

American Wood Council/Canadian Wood Council. 2013. North American LVL EPD. www.awc.org/pdf/greenbuilding/epd/AWC-EPD-LVL-1307.pdf. Accessed August 4, 2016.

APA—The Engineered Wood Association. 2014. Engineered wood statistics: Third quarter 2014. APA—The Engineered Wood Association, Tacoma, Washington. 9 pp.

ASTM International. 2010. Standard practice for categorizing wood and wood-based products according to their fiber source. ASTM D7612-10. ASTM International. West Conshohocken, Pennsylvania. pp. 783–793.

ASTM International. 2014a. Standard specification for evaluation of structural composite lumber products. ASTM D5456-14b. ASTM International, West Conshohocken, Pennsylvania. 33 pp.

ASTM International. 2014b. Standard guide for evaluating the attributes of a forest management plan. ASTM D7480-08. ASTM International, West Conshohocken, Pennsylvania. pp. 787–798.

Athena Sustainable Material Institute. 2016. Athena impact estimator for buildings. www.athenasmi.org/our-software-data/impact-estimator. Accessed August 4, 2016.

Baldwin, R. F. 1995. Plywood and Veneer-Based Products: Manufacturing Practices. Forest Products Society, Madison, Wisconsin. 388 pp.

Bare, J. C. 2011. TRACI 2.0: The tool for the reduction and assessment of chemical and other environmental impacts 2.0. *Clean Technol. Environ. Policy* 13:687–696.

Bergman, R. D. 2012. The effect on climate change impacts for building products when including the timing of greenhouse gas emissions. PhD dissertation. University of Wisconsin, Madison. 278 pp.

Bergman, R. D. and S. Alanya-Rosenbaum. 2017a. Cradle-to-gate life-cycle assessment of laminated veneer lumber produced in the Pacific Northwest region of the United States. CORRIM Final Report, Module H1. Revised April 2017. 92 pp.

Bergman, R. D. and S. Alanya-Rosenbaum. 2017b. Cradle-to-gate life-cycle assessment of laminated veneer lumber produced in the southeast region of the United States. CORRIM Final Report, Module H2. Revised April 2017. 89 pp.

Bergman, R. D., M. Puettmann, A. Taylor, and K. E. Skog. 2014. Carbon impacts of wood products. *Forest Prod. J.* 64(7/8):220–231.

Bergman, R. D. and A. M. Taylor. 2011. Environmental product declarations of wood products—An application of life cycle information about forest products. *Forest Prod. J.* 61(3):192–201.

Consortium for Research on Renewable Industrial Materials (CORRIM). 2005. Reports on environmental performance of wood building materials. *Wood Fiber Sci*. 37 (Special Issue).

Consortium for Research on Renewable Industrial Materials (CORRIM). 2010. Special issue second report March 2010. *Wood Fiber Sci*. 43 (Special Issue).

Consortium for Research on Renewable Industrial Materials (CORRIM). 2014. Research guidelines for life-cycle inventories (draft). University of Washington, Seattle. 40 pp.

FPInnovations. 2015. Product category rule (PCR): For preparing an environmental product declaration (EPD) for North American structural and architectural wood products. UN CPC 31, NAICS 321. https://fpinnovations.ca/ResearchProgram/environment-sustainability/epd-program/Documents/pcr-v2.pdf. Accessed August 4, 2016.

International Organization for Standardization (ISO). 2006a. Environmental labels and declarations—Type III environmental declarations—Principles and procedures. ISO 14025. ISO, Geneva. 25 pp.

International Organization for Standardization (ISO). 2006b. Environmental management—Life-cycle assessment—Requirements and guidelines. ISO 14044. ISO, Geneva. 46 pp.

International Organization for Standardization (ISO). 2006c. Environmental management—Life-cycle assessment—Principles and framework. ISO 14040. ISO, Geneva. 20 pp.

International Organization for Standardization (ISO). 2007. Sustainability in building construction—Environmental declaration of building products. ISO 21930. ISO, Geneva. 34 pp.

International Reference Life Cycle Data System. 2010. ILCD Handbook—General Guide for Life Cycle Assessment—Detailed Guidance. EUR 24708 EN. European Commission, Joint Research Centre, Institute for Environment and Sustainability. Publications Office of the European Union, Luxembourg. 417 pp.

Johnson, L. R, B. R. Lippke, J. D. Marshall, and J. Comnick. 2005. Life-cycle impacts of forest resource activities in the Pacific Northwest and Southeast United States. *Wood Fiber Sci*. 37(CORRIM Special Issue):30–46.

Kaestner, D. 2015. Life cycle assessment of the oriented strand board and plywood industries in the United States of America. Master's thesis. University of Tennessee, Knoxville. 122 pp. http://trace.tennessee.edu/utk_gradthes/3376. Accessed August 4, 2016.

National Renewable Energy Laboratory (NREL). 2012. Life-cycle inventory database project. www.lcacommons.gov/nrel/search. Accessed August 4, 2016.

PRé Consultants. 2016. SimaPro 8 life-cycle assessment software

http://prime-pdf-watermark.prime-prod.pubfactory.com/ | 2024-12-26

package. Version 8. Plotter 12. Amersfoort, The Netherlands. www.pre.nl. Accessed August 4, 2016.
Prestemon, J. P., D. N. Wear, and M. O. Foster. 2015. The global position of the U.S. forest products industry. e-General Technical Report SRS-204. USDA Forest Service, Southern Research Station, Asheville, North Carolina. 24 pp.
Puettmann, M., D. Kaestner, and A. Taylor. 2016a. Life cycle assessment of oriented strandboard (OSB) production. CORRIM Report, Module E. October. 56 pp.
Puettmann, M., D. Kaestner, and A. Taylor. 2016b. Life cycle assessment of softwood plywood production in the US Pacific Northwest. CORRIM Report, Module D. October. 55 pp.
Puettmann, M. E., R. D. Bergman, S. Hubbard, L. Johnson, B. Lippke, and F. Wagner. 2010. Cradle-to-gate life-cycle inventories of US wood products production: CORRIM Phase I and Phase II products. *Wood Fiber Sci*. 42(CORRIM Special Issue):15–28.
Puettmann, M. E., E. E. Oneil, J. Wilson, and L. Johnson. 2013a. Cradle to gate life cycle assessment of laminated veneer lumber production from the Pacific Northwest. Consortium for Research on Renewable Industrial Materials, University of Washington, Seattle. 23 pp.
Puettmann, M. E., E. E. Oneil, J. Wilson, and L. Johnson. 2013b. Cradle to gate life cycle assessment of laminated veneer lumber production from the Pacific Northwest. Consortium for Research on Renewable Industrial Materials, University of Washington, Seattle. 21 pp.
Ritter, M. A., K. E. Skog, and R. D. Bergman. 2011. Science supporting the economic and environmental benefits of using wood and wood products in green building construction. General Technical Report FPL-GTR-206. USDA Forest Service, Forest Products Laboratory, Madison, Wisconsin. 9 pp.
Stark, N. M., Z. Cai, and C. Carll. 2010. Wood-based composite materials: Panel products, glued-laminated timber, structural composite lumber, and wood–nonwood composite materials. *In:* Wood Handbook—Wood as an Engineering Material. General Technical Report FPL-GTR-113. USDA Forest Service, Forest Products Laboratory, Madison, Wisconsin. pp. 11-1–11-28.
US Census Bureau. 2012. 2012 North American Industry Classification System definitions. 321213 Structural wood product manufacturing. www.census.gov/eos/www/naics. Accessed August 4, 2016.
US Environmental Protection Agency (US EPA). 2002. AP 42 Section 10.9: Engineered wood products manufacturing. pp. 10.9-1–10.9-24. www.epa.gov/ttnchie1/ap42/ch10/final/c10s09.pdf. Accessed August 4, 2016.
Wilson, J. B. 2009. Resins: A life cycle inventory of manufacturing resins used in the wood composites industry. CORRIM Phase II Final Report, Module H, January. 103 pp. www.corrim.org/pubs/reports/2010/phase2/Module_H.pdf. Accessed August 4, 2016.
Wilson, J. B. 2010. Life-cycle inventory of formaldehyde-based resins used in wood composites in terms of resources, emissions, energy and carbon. *Wood Fiber Sci*. 42(CORRIM Special Issue):125–143.
Wilson, J. B. and E. R. Dancer. 2005. Gate-to-gate life-cycle inventory of laminated veneer lumber production. *Wood Fiber Sci*. 37(CORRIM Special Issue):114–127.

http://prime-pdf-watermark.prime-prod.pubfactory.com/ | 2024-12-26