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Cradle-to-Gate Life-Cycle Assessment of North American Laminated Strand Lumber Production

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Abstract

The world is facing severe challenges from climate change and resource scarcity caused by exponential growth in population and the rising standard of living. Raw materials for buildings and construction account for more than 35% of global primary energy use and nearly 40% of energy-related CO₂ emissions. The public as well as city, state, and national governments are interested in knowing the environmental impacts of materials including wood products. This study conducted a cradle-to-gate life-cycle assessment (LCA) of laminated strand lumber (LSL) production in North America (United States and Canada). System boundaries in this study included the following information modules: raw material extraction (A1), raw material transportation (A2), and product manufacturing (A3). Module A1 included forest resources and resin production. The declared unit was 1 m³ of LSL packaged and ready for shipment. Surveys were used to collect primary LSL production data. This LCA study followed the guidelines of the International Organization for Standardization standards and wood products product category rules. The tool for the reduction and assessment of chemical and other environmental impacts (TRACI), CML baseline, and cumulative energy demand were used to conduct a life-cycle impact assessment. The weighted average oven-dried density of LSL was 647 kg/m³. Results showed that about 275 kg CO₂eq (A1–A3) were released in the production of 1 m³ of LSL, with the A1 life-cycle stage accounting for 56%, followed by A3 (23%) and A2 (21%).

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Resin production contributed 124 kg/CO₂eq (45%), which is a substantial portion. Raw material extraction (A1), resource transport (A2), and LSL manufacturing (A3) consumed about 26%, 6%, and 68% of total cradle-to-gate primary energy, respectively. About 56% of the total primary energy used in the production of LSL (A1–A3) came from nonrenewables, mostly fossil resources. One cubic meter of LSL stores 1,150 kg CO₂eq, which is about four times more than the embodied carbon released from cradle to gate (275 kg CO₂eq).

Keywords: Wood, LCA, environmental product declaration, EPD, product category rule, engineered wood product, LSL, structural composite lumber

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Cradle-to-Gate Life-Cycle Assessment of North American Laminated Strand Lumber Production

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1 Executive Summary

1.1 Study Goals

The goal of this study was to perform a cradle-to-gate life-cycle assessment (LCA) and update the environmental impacts associated with 2019 laminated strand lumber (LSL) production in North America (United States and Canada). A comparative proclamation was not the goal of this study.

1.2 Methodology

This study followed the International Organization for Standardization (ISO) 14040 and 14044 standards, and Underwriter Laboratory Environment (ULE) product category rule (PCR) for North American structural and architectural wood products to develop a life-cycle inventory (LCI) and conduct an LCA. System boundaries in this study covered raw material extraction through LSL packaged for customer delivery. The LCI was developed considering the system modeling approach in which all input and output quantities are assigned to a reference flow, 1 m³ of LSL at the production gate. A declared unit (functional unit) of 1 m³ of LSL with a weighted average oven-dried density of 647.2 kg/m³ was used to translate the LCA results. Surveys were used to collect primary mill data, whereas secondary data were used from literature. The surveys collected all raw material inputs, outputs (product and coproducts), related direct emissions to water and air, and generation of solid waste. After the survey data were analyzed, multiple rounds of digital and telephonic communications were established with the representatives of the plants to verify numbers in the survey (if there were uncertainties about the appropriateness of values of certain information), and the numbers were revised based on the provided information. Secondary data were used from peer-reviewed literature and public databases. The LCA modeling software, SimaPro (contains DATASmart database) (PRé Sustainability, Amersfoort, the Netherlands),

was used to construct North American LSL LCI to perform life-cycle impact assessment (LCIA). The LCI development was preceded by a mass and energy balance that used a mass-allocation approach to assign environmental impacts to the product (LSL) and coproducts (mill residues burned on site or sold). The Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI) 2.1, CML baseline, and cumulative energy demand (CED) methods were used to determine the LCIA results and primary energy consumption, respectively.

1.3 Life-Cycle Inventory

The stages within the system boundary (cradle-to-gate) for LSL product production included resource extraction (A1), resource transportation (A2), and LSL manufacturing and packaging (A3). The forest resources extracted to make LSL consisted of logs from four hardwood species. The A1 stage included all upstream impacts from forest management and forestry operations. Cradle-to-gate methylene diphenyl diisocyanate resin production was also part of the A1 stage. The LCI flows listed raw materials consumed and emissions to nature.

1.4 Life-Cycle Impact Assessment

Several impact categories were examined as recommended by the ULE PCR for North American structural and architectural wood products. The main impact categories were global warming (GW) (kg CO₂eq), acidification (kg SO₂eq), eutrophication potential (EP) (kg Neq), ozone depletion potential (ODP) (kg chlorofluorocarbons (CFC)-11eq), photochemical smog (kg O₃eq), abiotic depletion potential for fossil resources (ADP fossil) (MJ), and fossil fuel depletion (MJ surplus). The LCI also provided additional information such as the use of primary energy resources consumption [energy consumption from sources that were nonrenewable (fossil fuels), nonrenewable (nuclear fuels), renewable (biomass), renewable (wind, solar, and geothermal) and renewable (hydro)], water use, and indicators describing waste.

1.5 Key Findings

Among all phases in the life cycle, the resource extraction phase (A1) contributed the most to the total cradle-to-gate environmental impact of LSL. The cradle-to-gate LCIA results (Table 1) showed that 274.9 kg CO₂eq was released in the production of 1 m³ of LSL. Considering biogenic carbon in GW impact resulted in the same value, 274.9 kg CO₂eq, because the wood resource was extracted from a sustainable source per ISO 21930. Each unit (1 m³) of LSL stores 1,150 kg CO₂eq (excluding additives). Resource extraction (A1), resource transport (A2), and LSL manufacturing (A3) consumed 25.5%, 6.4%, and 68.1% of total cradle-to-gate primary energy, respectively. Resin production contributed 124 kg/CO₂eq (45%), which is a substantial portion. About 55.6% of the total primary energy used in the production of LSL came from nonrenewables, especially fossil resources. This study estimated a lower environmental footprint (that is, GW impact) and primary energy use in the production of LSL compared with a previous study.

1.6 Sensitivity Analysis

A sensitivity analysis was completed per ISO 14040 standard to model the effects of raw material transport distance and consumption of energy including electricity, natural gas, diesel, gasoline, and starch for the production of LSL. In the sensitivity analysis, key inventory parameters were increased and decreased by 20% to investigate the effect on the LCIA results. This showed that a 20% change in electricity, adhesive, and on-site wood fuel usage had significant effects on the results. For example, a 20%

increase in on-site wood fuel can increase GW, ODP, and EP by 2%, 7%, and 3%, respectively, with a subsequent increase in renewable primary energy carrier used as energy (RPRE) of nearly 28%. Other inputs such as log transport distance, diesel, and natural gas use variations had minor impacts.

1.7 Interpretation

The results of this study provided the cradle-to-gate environmental impacts of LSL production. The authors compared energy inputs from the current study (2019 data) to the earlier study that used 2013 data. About a 8% decrease in the use of primary energy was observed in this study compared with the previous study. Compared with the earlier study, there was a 7% decrease in GW impacts.

1.8 Acknowledgments

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2 Introduction

The earth and human civilization are facing severe challenges from climate change and resource scarcity because of exponential growth in human population and

Table 1—Life-cycle impact assessment for 1 m³ of laminated strand lumber (A1–A3)

Impact category and primary energy consumption	Units	Total
Impact category		
Global warming potential – TRACI 2.1	kg CO ₂ eq	274.90
Global warming potential – w/ biogenic CO ₂	kg CO ₂ eq	274.90
Depletion potential of the stratospheric ozone layer	kg CFC11eq	6.72E–06
Acidification potential of soil and water sources	kg SO ₂ eq	1.70
Eutrophication potential	kg Neq	0.20
Formation potential of tropospheric ozone	kg O ₃ eq	39.51
Abiotic depletion potential for fossil resources (ADP fossil)	MJ, NCV ^a	4,015.88
Fossil fuel depletion	MJ surplus	597.92
Primary energy consumption		
Nonrenewable, fossil	MJ	4,016.52
Nonrenewable, nuclear	MJ	2,495.93
Renewable, biomass	MJ	4,844.94
Renewable, wind, solar, geothermal	MJ	82.23
Renewable, hydro	MJ	263.49
Total	MJ	11,707.10

^aNCV, net calorific value.

rising standard of living (Bringezu and others 2017). Raw materials, especially for buildings and construction account for more than 35% of global primary energy use and nearly 40% of energy-related CO₂ emissions (Abergel and others 2017). To overcome these challenges, nations are determined to achieve the United Nations goal of sustainable development. Citizens, societies, cities, states, and nations are showing interest in materials with lower environmental impacts. Because of environmental awareness and regulations, and the advent of environmental preferential purchasing (EPP), documenting the environmental performance of building products using life-cycle assessment (LCA) has become a widespread emergent global trend. Moreover, LCA studies are inevitable for various product certifications including green building certifications (Bergman and Taylor 2011, Ibáñez-Forés and others 2016). Scientific documentation such as environmental product declarations (EPDs) provides verified data on the environmental performance of products and services to stakeholders including architects and builders, consumers, regulating agencies, and policymakers (ISO 14025 (ISO 2006a)). LCA study not only provides the required environmental performance of the product but also identifies the environmental hot spots for continuous improvements in the manufacturing of products and services provided (ISO 14040 (ISO 2006b) and ISO 21930 (ISO 2017)). Periodic update of EPDs (every five years) is mandatory for products that fall under the scope of the various certifications and thus require new or updated LCA data (ISO 2017, ULE 2018).

The International Organization for Standardization (ISO) defines LCA as a multistep process and includes certain specific steps (in ISO 14040) such as (1) define goal and scope, (2) develop life-cycle inventory (LCI), (3) perform life-cycle impact assessment (LCIA), and (4) interpret results (Fig. 1). Each step in the LCA study is interconnected and can be repeated based on feedback loops, and results are produced to achieve the goals of a particular study.

The LCI step is the key component for conducting an LCA, which is the process of quantifying all inputs, including energy, fuel, and raw material requirements, and all environmental releases occurring within the system boundaries, such as emissions to air, water, and soil. The LCIA process uses models to characterize and assess the effects of environmental releases identified in the LCI in impact categories. The interpretation phase deals with the findings of the LCI and/or the LCIA evaluations to achieve the goal of the study, reach conclusions, and provide recommendations.

This LCA study followed ISO standards (ISO 14040, ISO 14044 (ISO 2006c), and ISO 21930) and wood products product category rules (PCR) (ULE 2018, 2019). This report forms the basis for the development of industry-average

EPD for laminated strand lumber (LSL) in North America. The tool for the reduction and assessment of chemical and other environmental impacts (TRACI) (Bare 2011), CML baseline (Institute of Environmental Sciences), and cumulative energy demand (CED) were used to conduct an LCIA and estimate the required indicators as defined by the PCR and ISO 21930. This LCA report focuses on the production of LSL in North America and uses facility data from the year 2019. Feedstocks (for example, wood resources inputs) for the production of LSL were sourced from the northeast–north central United States and central Canada regions. An attributional system modeling LCA approach was followed, and the LCI was developed using mass allocation. The LCI included all inputs (raw materials, energy, and fuel) and outputs (main products, coproducts, wastes, and direct emissions to air, soil, and water) associated with the manufacturing of LSL on a per-unit (that is, declared unit of 1 m³ of LSL) through careful consideration of the system boundary (cradle-to-gate).

2.1 Abbreviations

ADP	Abiotic depletion potential
CED	Cumulative energy demand
EPD	Environmental product declaration
GWP	Global warming potential
ISO	International Organization for Standardization
LCA	Life-cycle assessment
LCI	Life-cycle inventory
LCIA	Life-cycle impact assessment
LSL	Laminated strand lumber
MDI	Methylene diphenyl diisocyanate
OD	Oven-dry

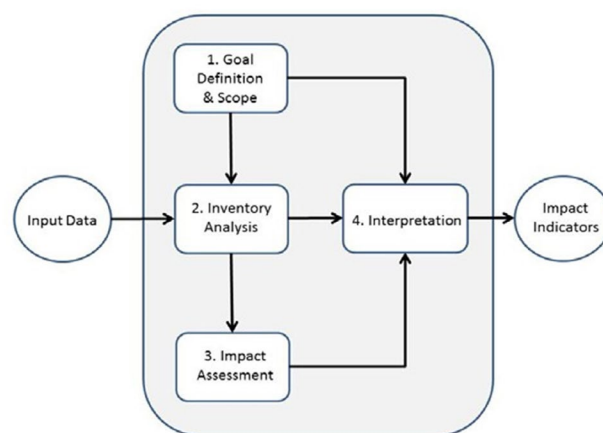


Figure 1. A life-cycle assessment approach and its basic steps (ISO 14040 (ISO 2006b)).

PCR	Product category rules
tkm	Metric ton – kilometer
TRACI	Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts

2.2 Glossary of Terms

Allocation — A way of dividing emissions and resource use among the different products of a process. The partitioning can be made on a weight basis, energy content, or economic value.

Cradle-to-gate — The LCA model includes the upstream part of the product life cycle, that is, all steps from raw material extraction to product at the factory gate.

Declared unit — Quantity of a wood building product for use as a reference unit (can be mass or volume) for the expression of environmental information needed in information modules.

Functional unit — Expresses the function of the studied product in quantitative terms and serves as a basis for calculations. It is the reference flow to which other flows in the LCA are related. It also serves as a unit of comparison in comparative studies.

Life-cycle assessment (LCA) — Method for the environmental assessment of products covering their life cycle from raw material extraction to waste treatment.

Life-cycle inventory (LCI) — An LCA study that goes as far as an inventory analysis but does not include impact assessment.

Life-cycle impact assessment (LCIA) — Phase of an LCA study during which the environmental impacts of the product are assessed and evaluated.

Product category rules (PCR) — Set of specific rules, requirements, and guidelines for the development of type III environmental declarations for one or more product categories (ISO 14025).

System boundary — A set of criteria that specifies which unit processes are part of a product system (adapted from ISO 14044).

3 Description of Product and Industry

3.1 LSL Products

LSL is a structural building material that falls within the general category of engineered wood products referred to as structural composite lumber (SCL). In LSL, strands with high aspect ratio are glued and compressed to form panels up to a thickness of 90 mm. Waterproof resin adhesives are used in the manufacture of LSL.

An example of LSL in residential use is shown in Figure 2. Most commonly, LSL is used in headers and beams, wall stud applications, roof beams and rafters, truss chords, rim boards, and stair stringers. The construction specification institute (CSI) codes for LSL are 06-11-00 (wood framing), 06-11-13 (engineered wood products), and 06-13-23 (heavy timber framing). The United Nations Standard Products and Services Codes (UNSPSC) for LSL are 30103602, 30103606, and 30103607. LSL is described by American Society for Testing and Materials (ASTM) D9-12 (Standard Terminology Relating to Wood and Wood-Based Products) (ASTM 2020). The production of LSL is evaluated according to ASTM D5456 (ASTM 2019), which includes other SCL products such as laminated veneer lumber and parallel strand lumber.

LSL uses smaller veneers or strands (203 to 254 mm) cut directly from whole logs. Waterproof adhesives are sprayed on the strands, cured with steam, and pressed with steam injection pressure. LSL is available in various dimensions (Table 2) of 38- to 89-mm thickness, 89- to 610-mm width, and length similar to lumber (CORRIM 2015, Craig and Abdullahi 2016).

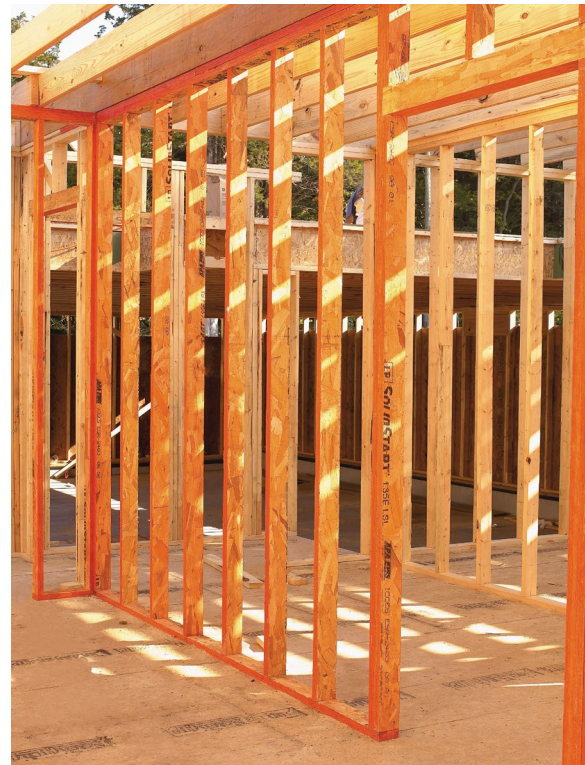


Figure 2. Example of application of laminated strand lumber in residential construction (Photo used with permission from Louisiana-Pacific Corporation, Nashville, Tennessee, USA).

Table 2—Dimensions and specifications of laminated strand lumber available in North America

Characteristics	Product specifications
Thickness	1-1/2 in., 1-3/4 in., 3-1/2 in.
Width	3-1/2 in., 4-3/8 in., 5-1/2 in., 7-1/4 in., 8-5/8 in., 9-1/4 in., 9-1/2 in., 11-1/4 in., 11-7/8 in., 14 in., 18 in., 20 in., 22 in., 24 in.
Grade	1.35E, 1.55E, 1.75E
Framing	Same as lumber sizes
End sealing	Edges and ends are sealed for additional moisture protection
Moisture content	4%–10% (dry basis)

3.2 Wood Species and Moisture Content

The material (mechanical and physical) properties of LSL are dependent on the density of panel, strand species, orientation of the strands, and glue used in the manufacturing process. In North America, LSL is usually manufactured from low quality and small-diameter hardwood trees. The primary species used are a mixture of aspen (*Populus tremuloides*), yellow birch (*Betula alleghaniensis*), and silver (*Acer saccharinum*) and sugar maple (*Acer saccharum*). The moisture content of the logs of these wood species varies between 45% and 48% dry basis (db) when procured by the mills. The moisture content (Table 1) of the main product varied between 4% and 10% db.

3.3 LSL Industry

Many engineered structural wood products have been developed in the last several decades, including LSL. LSL, oriented strandboard (OSB), and plywood were developed in response to increasing demand for high-quality wood products from the forest resource. SCL products are characterized by smaller pieces of wood glued together into sizes common for solid lumber. The outputs from the mills were LSL (main product) and coproducts such as strands and mill residues, including bark, trimmings, short strands, and log yard–pond debris. Generally, strands are sold to OSB mills, and mill residues are used to produce heat for internal use. The LSL production complex was modeled as a single-unit process. However, the detailed manufacturing process and unit operations (A3) to produce LSL are shown in Figure 3. This study did not include the impacts of plant infrastructure and equipment, maintenance, and end of life (Table 3).

At present, two LSL mills exist in North America (one in the United States and one in Canada). In North America, the 2019 annual production of LSL was 333,780 m³, which represented 100% of total LSL industry production (AWC 2020). The production was up 6.3% from 2013 (316,456 m³) (CORRIM 2015).

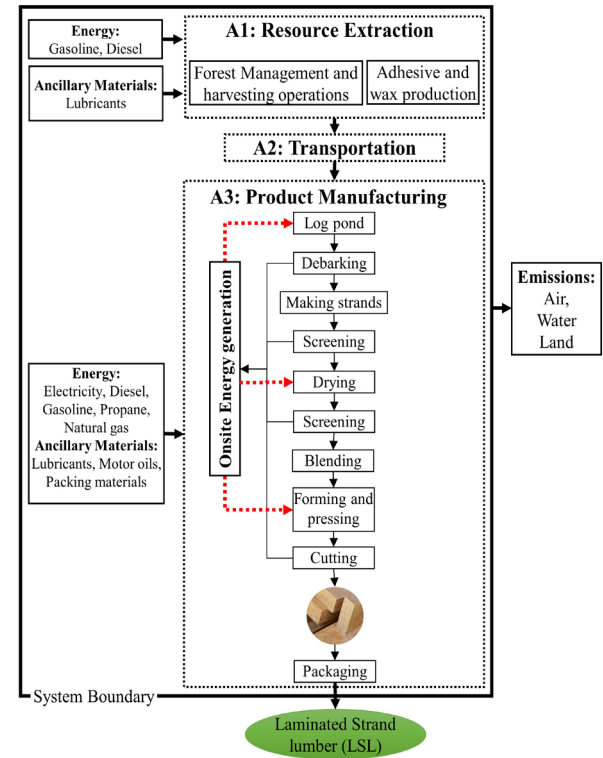


Figure 3. Cradle-to-gate system boundary of laminated strand lumber production in North America.

3.4 Typical Emission Control Measures by LSL Mills

Common emission control devices (ECD), such as cyclones, bag-houses, and electrified filter beds (EFBs), are used throughout the LSL manufacturing process. ECDs are used to decrease particulate and chemical emissions. No dangerous substances were reported by the industry as described in ISO 21930. LSL manufacturers typically generate minimal solid waste, which includes wood processing waste, plastic strapping and cardboard, metals, and other materials. Wood waste generated during

Table 3—System boundary inclusions and exclusions for cradle-to-gate laminated strand lumber production

Included	Excluded
• Production of upstream processes for all resources, raw materials, fuels, and energy for laminated strand lumber production • Transportation of materials throughout the cradle-to-gate manufacturing life stages • Packaging	• Fixed capital equipment and facilities • Transportation of employees • Construction, maintenance, use, and end-of-life treatment

processing was used for on-site energy generation to produce the heat needed for the drying and pressing processes. There are typically on-site water emissions, but mills also did not report any water emissions in this study. However, mills reported air emissions such as volatile organic compounds (VOCs), particulate matter, and hazardous air pollutants (HAPs).

4 Method

4.1 Goal

The goal of this study was to quantify the cradle-to-gate environmental impacts of producing LSL. Along with the environmental impacts, the PCR also mandated additional indicators such as energy use, waste generation, and many more (ULE 2019), which were also estimated in this study.

4.2 Scope

Following international ISO 14040 and 14044 standards, the scope of an LCA study covers the life-cycle stages of a product. The scope of this study was to cover the cradle-to-gate life-cycle stages of LSL production in North America. All inputs (material, fuel, and energy), outputs (product and coproducts), and direct emissions to air, water, and land were included in the development of the LCI and LCIA. Indirect emissions from the consumption of materials were included in secondary datasets available with the LCA software. Wood resources used in LSL production are obtained from hardwood logs from the northeast–north central (NE–NC) United States and central Canadian regions. Data for the LCI were based on actual manufacturing gate-to-gate inputs and outputs surveyed directly from LSL mills (Appendix A) and previously published data for cradle-to-gate forest resource LCIs (Oneil and others 2010, CORRIM 2015, Athena 2018).

4.3 Allocation Procedure

Multiple products are common in manufacturing systems. Therefore, an LCA study needs to select an allocation method for assigning environmental impacts for each product. Mass, energy, and economic allocation approaches are generally used for allocating various impacts to each output from a manufacturing system. The wood products PCR recommends using a mass allocation approach. All inputs and direct emissions were allocated to various outputs (LSL and its coproducts) based on their respective mass.

4.4 Functional and Declared Unit

The main purpose of the functional or declared unit is to provide a reference to which all inputs and outputs are related and to quantify the service delivered by the product system. The functional unit, used for the development of cradle-to-grave EPDs, covers all life-cycle stages of a product. A declared unit is used in place of a functional unit when the LCA study is partial (cradle-to-gate) and covers

the product life cycle up to the point of production of the product that is ready for delivery to the customer. A declared unit is used in instances where the function and the reference scenario for the whole life cycle of a wood building product cannot be stated (ISO 14044, ULE 2019). Under the PCR (ULE 2018, 2019), the declared unit for LSL is one cubic meter (1.0 m^3) of product ready for delivery to the customer. For the conversion of units from the U.S. industry measurement system, 1.0 cubic foot is equal to 0.02832 m^3 . All input and output data were allocated to the declared unit of the product based on the mass of products and coproducts following standards for conducting LCAs (ISO 21930).

4.5 Intended Audience

The primary audience for the LCA report includes LSL manufacturers, American Wood Council, Canadian Wood Council, building developers and owners, architects, and other LCA practitioners.

4.6 Comparative Assertions

According to ISO 14044, and the wood products PCR (ULE 2019), the LCA boundary would need to be expanded to include the use and end-of-life phases if future comparative studies are intended to be disclosed to the public. This report did not include the use (B1–B7) and end-of-life (C1–C4) phases of products, which are required for comparative assertions relative to substitute products. Therefore, this study will not be used for comparative analysis without further analysis that expands the system boundary to the end-of-life phase of LSL.

4.7 System Boundaries

The cradle-to-gate system boundary of LSL is shown in Figure 3. The system boundary begins with resource extraction and ends with LSL packaged and ready to leave the mill (at the gate).

The system boundary of LSL included resource extraction (A1), transportation (A2), and product manufacturing (A3). The resource extraction stage (A1) included natural regeneration, management, and the final harvest. Cradle-to-gate methylene diphenyl diisocyanate (MDI) resin production was also part of the A1 stage. Harvested logs were transported (A2) either on trucks or rail to the LSL mills. Logs were broken down into strands and further processed to make LSL (A3), which was then packaged for shipment to customers (Fig. 3). The LSL manufacturing (A3) phase is a multistep operation including log yard operations, debarking, making strands, LSL production, and final packaging of the product. Outputs to the system boundary include 1 m^3 of LSL ready to be shipped, air and water emissions, solid waste, and coproducts. In this case, coproducts, especially a certain portion of the mill residues, are used internally to produce

heat for internal use. The coproducts are no longer tracked after they leave the system boundary.

4.8 Cut-Off Rules

According to ISO 21930, if the mass–energy of a flow is less than 1% of the cumulative mass–energy of the model flow, it may be excluded, provided its environmental relevance is minor (ISO 2017, ULE 2019). 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. Under Title III of the Clean Air Act Amendments of 1990, the U.S. Environmental Protection Agency (EPA) has designated HAPs that wood products facilities are required to report as surrogates for all HAPs. These are methanol, acetaldehyde, formaldehyde, propionaldehyde (propanal), acrolein, and phenol. All HAPS are included in the LCI; no cut-off rules apply. There were no cut-offs used in the impact assessment.

4.9 Description of Processes and Life-Cycle Inventories

4.9.1 A1: Resource Management: Forest and Other Inputs

Whole hardwood logs were used to manufacture LSL in North America. The production of the logs began in the forest and included the forestry activities that are customary to central Canada (Athena 2018) and NE–NC United States (Oneil and others 2010, CORRIM 2015). Post-harvest and stand establishment activities such as site preparation and planting scenarios vary substantially by owner group and region. The hardwood forest for this region did not include slash reduction activities and assumed natural regeneration of the forest (Oneil and others 2010). The harvest included felling, skidding, processing, and loading for both commercial thinning and final harvest operations.

The weighted average allocation to different processes considers inherent differences in site productivity and energy usage by different kinds of logging equipment. Table 4 shows the contribution of the different regions that supply hardwood logs to produce LSL in North America. The weighted average density of incoming logs was 385.06 oven-dry (OD) kg/m³, far less than the final product, which has an expected range of 625 to 700 kg/m³ depending on the grade of the LSL produced (Craig and Abdullahi 2016, Aro and others 2016). This difference is from the substantial pressing of the mat into the billet.

In addition to the forest resources, the A1 phase included the procurement of all other inputs including MDI resin and ancillary materials. Thus, the A1 phase considered the impacts in the production and handling of these inputs.

Table 4—Wood feedstock types and source for input for 1 m³ laminated strand lumber production (unallocated)

Feedstocks by region	Ovendry kg/m ³	Contribution (%)
Hardwood, logs, U.S. Northeast	894.62	24.8
Hardwood, logs, Canada	977.21	75.2
Total: North American average	956.76	100

Table 5—Weighted average delivery distance (one-way) for materials to laminated strand lumber mill

Input material	Mode of transport	Weighted transport distance (km)	Weighted coefficient of variation (CoV _w) (%)
Feedstocks			
Hardwood, logs	Truck	204.16	51.4
	Rail	41.09	246.5
Nonfeedstock materials			
Resins	Rail	2,170.19	50.6
Ancillary material	Truck	1,015.94	73.2
	Rail	157.19	246.5
Other material	Truck	824.20	27.7

4.9.2 A2: Feedstocks and Material Transport

Harvested logs were transported by trucks and rail from the forest to the mill. Resins and various ancillary materials and additives are used in the production of LSL, and these materials were also transported in trucks as well as rail. Table 5 shows the weighted-average haul distance for feedstocks and other materials used in the manufacturing of LSL.

4.9.3 A3: LSL Manufacturing

The LSL manufacturing process is highly automated, process-controlled, and fairly linear as illustrated in Figure 4 (Craig and Abdullahi 2001, Moses and others 2003, Stark and others 2021, Moradpour and others 2018). The major unit operations were storage of logs; log pond; debarking; stranding; drying; screening; blending; forming; hot (steam) pressing; cutting, trimming, and sanding; and packaging. After the logs reach the mill, the manufacturing process of LSL begins with a whole log, which is debarked after softening in a heated log pond and then processed through the rotating knives of a stranding machine. Strands are screened, dried, and screened again in preparation for the bonding process. The strands are bonded together using a waterproof adhesive sprayed on the stands in a rotating drum. The strand–resin–adhesive mat is cured using steam and pressure, and then the LSL panels are cut to size and receive a protective end [edge] seal before packaging and shipping. All flow analyses of wood and bark in the process were determined on an OD weight basis of 647.2 OD kg/m³ (including additives). Although this density on an oven-dried basis was much higher than the incoming logs, it is

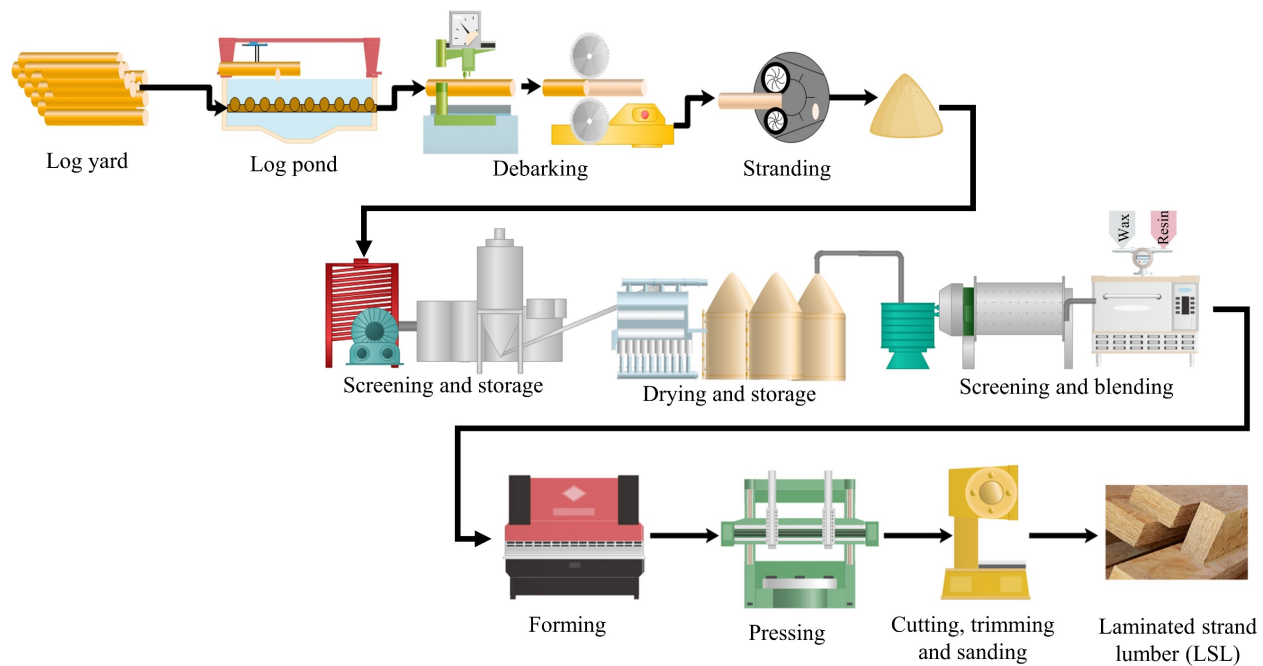


Figure 4. Process flow diagram of the manufacturing process of laminated strand lumber.

consistent with what is reported by Denizli-Tankut and others (2004), Craig and Abdullahi (2016), and Tripathi and Rice (2017).

4.9.3.1 Storage Yard

Logs are delivered to the mill in a long (tree length) form or shorter bolts ranging from 2.5 to 2.6 m long. Logs are unloaded by large mobile equipment and stacked in the yard in a “first in first out” inventory method. The storage yard acts as a buffer for the mill, and all feedstock is weight-scaled and moisture contents are determined. Logistics equipment such as log stackers or front-end loaders are used to move logs from the storage yard to the mill. Additional mobile equipment is used to move all feedstock for further processing. In this study, inputs included for the operations in the storage yard were woody feedstocks, electricity, fuel, and lubricants. Outputs were feedstock moved to mills.

4.9.3.2 Log Pond, Debarking, and Stranding

Mills in the north typically use hot ponds to raise the temperature of the wood to about 20°C before debarking. If the wood is tree length, it is cut to shorter pieces either before or after debarking. Debarking is done either by ring or drum debarkers, and the bark is used by the mills as fuel or sold as a coproduct. The bolts of wood then move to the stranders, which reduce them to thin strands 0.8 to 1.3 mm thick, 300 to 330 mm long, and 19 to 38 mm wide. Some mills have disc screens installed after the stranders to remove small unacceptable particles before drying. These small particles are used for fuel or sold. The acceptable strands then go to the green bins (CORRIM 2015).

4.9.3.3 Drying and Screening

Strands are fed from the green bins to the dryers to decrease their moisture content. Depending on the species, green moisture content can range from 50% to more than 100%, OD basis. The dryers decrease the moisture content of strands to less than 2% or 3%. The emissions from the dryers contain water, small wood particles, and VOCs. The dryers in the LSL process are usually single-pass rotary drum dryers. The dryer inlet temperature can range from 300 to 500 °C. Heated air is blown through the mass of strands until the desired moisture content is achieved, which typically takes 20 to 25 min (CORRIM 2015). Dry strands are sent to a dry storage bin where they are further processed by primary and secondary screens to sort them by size, and then they are stored in separate bins. Undersized and otherwise unsuitable strands are sent to either the OSB storage bin (and sold to an OSB manufacturer) or the dry biomass storage bin for use as wood fuel.

4.9.3.4 Blending

Screened strands are sent to rotary drum blenders where droplets of adhesive and wax are applied to the strand surfaces (CORRIM 2015). Either an emulsified wax or slack wax (molten wax) is applied using spray nozzles. The adhesive is MDI, which is listed on the EPA toxics release inventory (EPA 2020). Zinc borate is also added to the blend here, which helps prevent fungal decay and provides termite resistance. Based on the OD weight of LSL, adhesive content is usually between 3% and 4% and wax

content is less than 1%. The strands exit the blenders and are sent to forming bins.

4.9.3.5 Forming

The blended furnish is fed onto conveyors at the infeed to the forming bin. These conveyors move from one side of the forming bin to the other in a regular motion. The purpose is to ensure uniform mass distribution side-to-side in the forming bins. The forming bins feed strands onto “orienters”, the purpose of which is to orient the strands in the long direction of the product (machine direction). All strands in the composite are oriented in this direction. Mechanical weigh scales can be used to determine the variability of the mass distribution in both the machine and cross-machine directions (CORRIM 2015). After the mat is formed, a release agent is sprayed on the surfaces of the mat just before it enters the press to prevent it from sticking to the press platens.

4.9.3.6 Hot Pressing

The LSL process uses a single-opening steam-injection press, which allows efficient curing of adhesive in thick products (CORRIM 2015). A steam-injection press has heated platens, and temperature is maintained between 375 and 410 °C by circulating hot oil through a labyrinth built into the platen. However, the unique feature of steam-injection pressing is that the internal structure of the platens contains a second separate labyrinth of channels that allow the circulation of steam through the platen. The injection of steam allows extremely fast curing of the adhesive. Because LSL is commonly made with thicknesses greater than 75 mm, the cycle times would be excessive if hot presses were used without the steam-injection feature. After the adhesive is sufficiently cured, the press opens and the billet (product) is removed (CORRIM 2015).

4.9.3.7 Cutting, Trimming, Sanding, and Packaging

After cooling, the billets are stacked for further processing. Depending on customer requirements, finishing can be as simple as trimming the edges and ends, strapping, and shipping. Other products might require sanding (one or both sides), cutting to typical dimension lumber sizes, or cutting to special sizes requested by the customer. Trimming

residues and sander dust are usually used as fuel but could be sold as a byproduct. Rejected billets are either sold at a discount or broken into small pieces and used as fuel.

Finally, LSL is stacked and packaged before transporting the product to the customers. The packaged materials include wooden spacers, plastic wrap, and cardboard (Table 6). Forklifts are used to load trucks or rail cars for shipping.

4.9.3.8 On-Site Energy (Heat, Electricity, and Fuel) Inputs

Energy to produce LSL comes from mill residues (bark, hogged fuel) and fossil resources such as natural gas. Other fuels such as diesel, liquid propane gas, and gasoline are used to operate transport equipment within the mill. Electricity is used to operate equipment within the plant, including conveyors, refiners, fan motors, hydraulic press motors, sanders, pumps, and emission control systems. Electricity is used throughout the process.

Natural gas is used for the start-up of fluidized bed combustors (FBC) and supplemental heat for the thermal oil system (TOS). Wood fuels are used for FBC that supply heat to dryers and the TOS. Weighted average energy inputs consumed at the LSL manufacturing site were developed from survey data. Table 7 shows the energy inputs for the mill in the manufacturing of LSL. Wood fuel was the primary heating source used in the LSL process including the heat for drying strands, heating steam or oil for log ponds, and hot pressing. Wood fuel was mainly in the form of bark, wet and dry wood waste obtained after screening, and particulates collected in bag-houses. The heating value for wood is 20.9 MJ/kg (OD wood) (Puettman and Milota 2017).

4.10 Material Flows in LSL Production

To evaluate data quality, a weighted average mass balance of the LSL plants was performed (Table 8). In performing the mass balance for LSL, a system modeling approach was used and all inputs and outputs were considered. The weighted-average density of logs was 385.06 OD kg/m³, which was based on the four wood species used as feedstock.

Table 6—Materials used in packaging and shipping per cubic meter laminated strand lumber (LSL), North American average (unallocated)

Material	Value (kg/m ³ LSL)	CoV _w ^a (%)
Plastic strapping	0.045	228.0
Plastic packaging (bags)	0.004	246.5
Plastic packaging (wrap)	0.049	246.5
Wooden spacers	0.433	246.5
Cardboard spacers	0.114	81.1
Total	0.532	—

^aCoV_w, weighted coefficient of variation.

Table 7—On-site energy inputs per cubic meter laminated strand lumber, North American average (unallocated)

Inputs	Unit	Quantity	CoV _w ^a (%)
Electricity	kWh	276.01	1.27
Wood fuel	OD kg	264.56	30.10
Propane	L	9.78	244.19
Natural gas	m ³	0.40	81.13
Diesel	L	2.48	1.08
Gasoline	L	0.01	246.50

^aCoV_w, weighted coefficient of variation.

Table 8—Mass balance of laminated strand lumber manufacturing system

	Oven-dry mass (kg)	Contribution (%)	Weighted coefficient of variation (CoV _w) (%)
Inputs			
Feedstock			
Logs, aspen	867.17	87.53	1.21
Logs, yellow birch	49.71	5.02	48.03
Logs, hard maple	19.94	2.01	246.50
Logs, soft maple	19.94	2.01	246.50
Total, feedstock	956.76	96.6	—
Additives			
Wax	0.61	0.06	246.50
Adhesive (MDI)	30.82	3.11	6.06
Zinc borate	0.26	0.03	23.69
Emulsified wax	2.27	0.23	81.13
Total, additives	33.96	3.43	—
Total inputs	990.71	100	—
Outputs			
Products			
LSL	647.21	65.33	2.70
Coproducts			
Strands	32.59	3.29	81.13
Log yard–pond debris	22.49	2.27	81.13
Hog fuel	43.92	4.43	81.13
Bark	210.70	21.27	18.75
Short strands	7.43	0.75	0.00
Wood residues	9.46	0.95	246.50
Other wood residues	16.92	1.71	81.13
Total, coproducts	343.51	34.67	—
Total outputs	990.71	100	—

Table 9 gives detailed descriptions of the inputs (materials, transport, fuels, and energy) and outputs (main products, coproducts, emissions, and waste) crossing the system boundary of LSL. For materials, wood feedstocks included hardwood logs and additives. Wood fuel at 264.56 OD kg/m³ was mainly comprised of bark. The mass of bark itself at 211 OD kg/m³ was most likely high because bark typically comprises roughly 10% of logs. This uncertainty came from the fact that the bark was weighed after log conditioning (saturated with water) but one mill reported bark at 50% MC wet basis and the requirement to have clean logs for stranding (greater levels of debarking).

Electricity consumed on site was calculated to be 276 kWh/m³. Natural gas and propane were the primary fossil fuels used on site. Air emissions were derived from the surveyed mills along with pertinent emissions data

categorized by the EPA. When available, surveyed air emission data as primary data were selected rather than secondary data.

4.11 Data Collection

There were only two LSL manufacturing facilities in North America in the year 2019, and this study relied on participation from both mills. The LCA for LSL contains three life-cycle phases or processes (1) forest management and harvesting, (2) resource and material transportation, and (3) LSL manufacturing. Primary and secondary data were used in all these phases.

4.12 Primary and Secondary Data Sources

Primary data for the LCI were collected through surveys following ISO 14040 standards. This study relied almost exclusively on production and emissions data provided by

Table 9—The material and energy inputs and outputs crossing the system boundary of laminated strand lumber (LSL)

Inputs–outputs	Value	Unit	Mass allocation (%)
Inputs — materials and fuels			
Roundwood (logs)	956.76	OD kg/m ³	
Wax	0.61	kg/m ³	
Adhesive (MDI)	30.82	kg/m ³	
Zinc borate	0.26	kg/m ³	
Emulsified wax	2.27	kg/m ³	
Electricity, at grid	276.01	kWh/m ³	
Wood fuel	264.56	kg/m ³	
Propane, combusted in industrial equipment	9.78	L/m ³	
Natural gas, combusted in industrial boiler, direct-fired	0.40	m ³ /m ³	
Diesel, combusted in industrial equipment	2.48	L/m ³	
Gasoline, combusted in equipment	0.01	L/m ³	
Sealant	0.38	kg/m ³	
Release agent	1.04	kg/m ³	
Motor oil	0.02	kg/m ³	
Greases	0.01	kg/m ³	
Hydraulic fluid	0.19	kg/m ³	
Antifreeze	0.13	L/m ³	
Lubricating fluid	0.07	kg/m ³	
Transport, combination truck, diesel power, wood feedstock	626.52	tkm/m ³	
Train, wood feedstock	12.45	tkm/m ³	
Transport, combination truck, diesel power, resins	0.00	tkm/m ³	
Train, resins	133.75	tkm/m ³	
Transport, combination truck, diesel powered, ancillary material	10.20	tkm/m ³	
Train, ancillary materials	0.99	tkm/m ³	
Inputs — water			
Water, municipal	205.43	L/m ³	
Outputs — products and coproducts			
LSL	647.21	OD kg/m ³	65.33
Strands	32.59	OD kg/m ³	3.29
Log yard–pond debris	22.49	OD kg/m ³	2.27
Hog fuel	43.92	OD kg/m ³	4.43
Bark	210.70	OD kg/m ³	21.27
Short stands	7.43	OD kg/m ³	0.75
Wood residues	9.46	OD kg/m ³	0.95
Other wood residues	16.92	OD kg/m ³	1.71
Outputs — emissions to air			
Acetaldehyde ^a	3.10E–03	kg/m ³	
Acrolein ^a	7.07E–04	kg/m ³	
Benzene ^b	4.47E–05	kg/m ³	
Carbon monoxide ^a	6.90E–02	kg/m ³	
Carbon dioxide, biogenic ^b	4.85E–02	kg/m ³	
Dust (wood) ^b	1.49E–01	kg/m ³	
Formaldehyde ^a	2.72E–03	kg/m ³	

Table 9—The material and energy inputs and outputs crossing the system boundary of laminated strand lumber (LSL)—continued

Inputs–outputs	Value	Unit	Mass allocation (%)
Hydrogen chloride ^b	3.10E–04	kg/m ³	
Lead ^a	8.15E–06	kg/m ³	
Mercury ^a	1.21E–06	kg/m ³	
Methane ^b	3.00E–04	kg/m ³	
Methane, biogenic ^b	5.90E–03	kg/m ³	
Methanol ^b	2.10E–03	kg/m ³	
Methylene diisocyanate ^b	4.30E–03	kg/m ³	
Nitrous oxide (NO _x) ^b	2.91E–01	kg/m ³	
Dinitrogen monoxide (N ₂ O) ^a	7.09E–02	kg/m ³	
PM2.5	3.68E–02	kg/m ³	
Particulates, PM10-PM2.5 ^a	9.23E–02	kg/m ³	
PM10 ^a	1.65E–01	kg/m ³	
Particulates, unspecified ^a	2.74E–02	kg/m ³	
Phenol ^b	3.30E–03	kg/m ³	
Propionaldehyde (propanal) ^b	2.70E–03	kg/m ³	
Sulfur dioxide ^a	3.95E–02	kg/m ³	
Volatile organic compounds ^a	3.65E–01	kg/m ³	
Outputs — waste to treatment			
Wood waste	0.239	OD kg/m ³	
Boiler ash	7.995	kg/m ³	
Recycled metals	0.471	kg/m ³	
Plastic strapping	0.006	kg/m ³	
Cardboard	0.023	kg/m ³	
Paper	0.002	kg/m ³	
Batteries	0.00010	kg/m ³	

^aEmissions data are from survey data.

^bEmissions data are estimated from U.S. Environmental Protection Agency's air emissions factors for engineered wood products manufacturing (EPA 2002), from the previous study (CORRIM 2015), or from the literature (Puettmann and Milota 2017).

LSL producers in North America. CORRIM (2015) and another source (EPA 2002a, 2002b) were used to supplement the emissions data not provided by the mills. The secondary data on forest management and harvesting used in this study was modified from earlier studies to reflect species management (Oneil and others 2010). The original data included a weighted-average of various harvesting and forest management methods used in the NE–NC region. The secondary data on transport, fuels, and forest resource activities were obtained from DATASmart (LTS 2019), and electrical grid inputs were obtained from Ecoinvent 3.6 (Ecoinvent, Zurich, Switzerland), which represents the data for the North American region. The survey data represented LSL production in terms of input materials, electricity and fuel use, and emissions for the 2019 production year.

4.13 Secondary Data Sources

Databases with similar technology and geographical regions were used in this study. Primary data were not collected for various resource inputs including wood resource production, wood resource transport, and adhesive and wax production. Sources for secondary data are listed in Table 10.

4.14 Calculation Rules

LSL production is commonly reported in cubic feet in North America. The data from the surveys were assimilated and converted to a unit production basis of volume in the SI unit of cubic meters. One cubic foot of LSL equals 0.02832 m³ with an oven-dried moisture content of 4% to 10% (wet basis). Similarly, all input data were converted to SI units, and weighted-averages of input data were calculated based

Table 10—Secondary data sources and data quality assessment

	LCI data source	Region	Year	Data quality assessment
A1: Raw material inputs				
Inputs				
Forestry and harvesting: logs	Database: US EI 2.2 DATASmart (LTS 2019) for US and (ATHENA 2018) for Canada Process: For US region: Roundwood, hardwood, average, low-intensity management, NE-NC NREL/RNA U For Canada region: Roundwood, hardwood, low-intensity management, Canada [include fuel and lubricants only from table 4 of this (ATHENA 2018) report]	North America –region specific	2005–2019	<i>Technology:</i> Good. Process models region-specific technology. <i>Time:</i> Good. Some data are less than 10 years old. <i>Geography:</i> Good. Data are representative of regional production.
Adhesive-MDI	Database: US EI 2.2 DATASmart (LTS 2019) Process: Methylene diphenyl diisocyanate, at plant/US- US-EI U	North America	2019	<i>Technology:</i> Good. Process models average North American technology. <i>Time:</i> Good. Data are less than 10 years old. <i>Geography:</i> Good. Data are representative of North American production and combustion.
Wax and emulsified wax	Database: CORRIM data Process: Slack Wax AWC	North America	2012	<i>Technology:</i> Good. Process models average North American technology. <i>Time:</i> Good. Data are less than 10 years old. <i>Geography:</i> Good. Data are representative of North American production and combustion.
A2: Raw material transportation				
Inputs				
Truck transport	Database: US EI 2.2 Process: Transport, combination truck, Diesel-powered NREL/US U	North America	2019	<i>Technology:</i> Very good. Process models average North American technology. <i>Time:</i> Very good. Data are less than 5 years old. <i>Geography:</i> Very good. Data are representative of North American trucking.
Rail transport	Database: US EI 2.2 Process: Transport, train, diesel powered NREL/US U	North America	2019	<i>Technology:</i> Very good. Process models average North American technology. <i>Time:</i> Very good. Data are less than 5 years old. <i>Geography:</i> Very good. Data are representative of North American Rail.
A3: Manufacturing				
Power and energy inputs				
Electricity	Database: Ecoinvent 3.6 Process: Electricity, low voltage [NPCC, US only] market for Cut-off, U Electricity, low voltage (CA-ON) market for Cut-off, U	North America –region specific	2019	<i>Technology:</i> Very good. Process models average electricity technology specific to regional grids. <i>Time:</i> Very good. Data are less than 5 years old. <i>Geography:</i> Very good. Data are representative of regional electricity generation in North America.
Propane	Database: US EI 2.2 DATASmart (LTS 2019) Process: Natural gas, combusted in industrial equipment NREL/RNA U	North America	2019	<i>Technology:</i> Very good. Process models average North American technology. <i>Time:</i> Very good. Data are less than 5 years old. <i>Geography:</i> Very good. Data are representative of North American propane production and combustion.
Natural gas	Database: US EI 2.2 DATASmart (LTS 2019) Process: Natural gas, combusted in industrial boiler NREL/US U	North America	2019	<i>Technology:</i> Very good. Process models average North American technology. <i>Time:</i> Very good. Data are less than 5 years old. <i>Geography:</i> Very good. Data are representative of North American natural gas production and combustion.

Table 10—Secondary data sources and data quality assessment—continued

	LCI data source	Region	Year	Data quality assessment
Gasoline	Database: US EI 2.2 DATASMART (LTS 2019) Process: Gasoline, combusted in equipment NREL/US U	North America	2019	<i>Technology:</i> Very good. Process models average North American technology. <i>Time:</i> Very good. Data are less than 5 years old. <i>Geography:</i> Very good. Data are representative of North American gasoline production and combustion.
Diesel	Database: US EI 2.2 DATASMART (LTS 2019) Process: Diesel, combusted in industrial equipment NREL/US U	North America	2019	<i>Technology:</i> Very good. Process models average North American technology. <i>Time:</i> Very good. Data are less than 5 years old. <i>Geography:</i> Very good. Data are representative of North American diesel production and combustion.
Ancillary materials and packaging				
Hydraulic fluid, lubricating oil, greases and oils	Database: US EI 2.2 DATASMART (LTS 2019) Process: Lubricating oil, at plant/US- US-EI U	North America	2019	<i>Technology:</i> Very good. Process models average North American technology. <i>Time:</i> Very good. Data are less than 5 years old. <i>Geography:</i> Very good. Data are representative of North American processes.
Sealant	Database: US EI 2.2 DATASMART (LTS 2019) Process: Alkyd paint, white, 60% in H ₂ O, at plant/US- US-EI U	North America	2019	<i>Technology:</i> Good. Process models average North American technology. <i>Time:</i> Very good. Data are less than 10 years old. <i>Geography:</i> Very good. Data are representative of North American production and combustion.
Zinc borate	Database: US EI 2.2 DATASMART (LTS 2019) and Ecoinvent 3.6 Process: Zinc oxide, at plant/US- US-EI U; Boric oxide (GLO) production Cut-off, U; Water, deionised, at plant/US US-EI U	Global and North America	2019	<i>Technology:</i> Good. Process models average North American technology. <i>Time:</i> Very good. Data are less than 10 years old. <i>Geography:</i> Very good. Data are representative of North American and global production and combustion.
Antifreeze	Database: US LCI DATASMART (LTS 2019) Process: Antifreeze, ethylene glycol diluted to 50% / L / CORRIM	North America –region specific	2005–2019	<i>Technology:</i> Good. Process models region-specific technology. <i>Time:</i> Good. Some data are less than 10 years old. <i>Geography:</i> Very good. Data are representative of regional production.
Plastic strap	Database: US EI 2.2 DATASMART (LTS 2019) Process: Polyethylene, HDPE, granulate, at plant/US- US-EI U	North America	2019	<i>Technology:</i> Very good. Process models average North American technology. <i>Time:</i> Very good. Data are less than 5 years old. <i>Geography:</i> Very good. Data are representative of North American processes.
Wrapping material	Database: CORRIM data Process: Packaging - Wrapping material, EWP	North America	2014	<i>Technology:</i> Good. Process models average North American technology. <i>Time:</i> Good. Data are less than 10 years old. <i>Geography:</i> Good. Data are representative of North American processes.
Wooden spacers	Database: CORRIM data Process: Sawn lumber, hardwood, planed, kiln dried, at planer mill, NE-NC/m3	North America	2018	<i>Technology:</i> Very good. Process models average North American technology. <i>Time:</i> Very good. Data are less than 5 years old. <i>Geography:</i> Very good. Data are representative of North American processes.
Cardboard	Database: CORRIM data Process: Cardboard - EWP	North America	2014	<i>Technology:</i> Good. Process models average North American technology. <i>Time:</i> Good. Data are less than 10 years old. <i>Geography:</i> Good. Data are representative of North American processes.

on total LSL outputs of the two surveyed production facilities. This approach resulted in an LSL complex that represents a composite of the North American mills surveyed but may not represent any mill in particular. DATASmart (LTS 2019) and EcoInvent 3.6 databases were used to assess off-site impacts associated with the materials and energy used. SimaPro version 9.1 (PréConsultants 2020) was used as the accounting program to track all of the materials. The primary data obtained from the surveys were weight-averaged using the following formula:

$$\bar{P}_w = \frac{\sum_{i=1}^N P_i x_i}{\sum_{i=1}^N x_i} \quad (1)$$

Where $\bar{P}_w$ is the weighted average of the values reported by N mills, P_i is the reported i mill's value such as production, and x_i is the fraction of the mill's value to the combined total production of all the surveyed mills. Because the data from the surveyed mills varied between facilities, a statistical analysis was conducted. In this study, the weighted coefficient of variation was calculated (NIST-ITL 1996). The weighted coefficient of variation (CoV_w) is the weighted standard deviation (sd_w) divided by the weighted mean $\bar{P}_w$:

$$CoV_w = \frac{\sqrt{\left(\sum_{i=1}^N w_i \times (x_i - \bar{x}_w)^2 \right) / \left[\left((N' - 1) \sum_{i=1}^N w_i \right) / N' \right]}}{\bar{P}_w} \quad (2)$$

Where w_i is the weight of the i th observation, N' is the number of nonzero weights, and $\bar{x}_w$ is the weighted mean of the observations (N). Whenever missing data occurred for survey items, they were checked with facility personnel to determine whether it was an unknown value or zero. Missing data were carefully noted to ensure they were not averaged as zeros. Any outliers were resolved by contacting mill personnel.

4.15 Data Quality Requirements

This study collected data from LSL manufacturers in North America that use industry-standard technology. Primary data for the LCI were collected through surveys following ISO 14040. The production facilities surveyed were selected to be representative (100% of the total LSL industry) of North American production practices. The participating plants also provided information and data on the use of MDI resins, wax, fuels, energy consumption, electricity use, and ancillary inputs (lubricants, oils, greases, packaging, antifreeze, sealant, etc.).

4.16 Life-Cycle Impact Assessment

4.16.1 Method

The LCIA is the crucial phase of the LCA study because it establishes links between the LCI results and potential environmental impacts. The magnitude and significance of

the potential environmental impacts as a set of indicators are evaluated based on the LCI using the TRACI, CED, and CML methods. These impact indicators provide general, but quantifiable, indications of potential environmental impacts.

Each impact indicator is a measure of an aspect of a potential impact. This LCIA does not make value judgments about the impact indicators, meaning comparison indicator values are not valid. Additionally, each impact indicator value is stated in units that are not comparable with others. For the same reasons, indicators should not be combined or added. Additionally, the LCIA results are relative expressions and do not predict impacts on category endpoints, the exceeding of thresholds, safety margins, or risks. The primary fuels are categorized into nonrenewable (fossil and nuclear) and renewable (biomass, geothermal, solar, wind, and hydro).

The required indicators recommended by the PCR and ISO 21930 are shown in Table 11. The target impact indicator, the impact category, and the means of characterizing the impacts are subsequently summarized. The term global warming potential is used in this report to be consistent with the building product PCR (ULE 2018) and ISO 21930. However, GWP refers to the heat trapping capacity of a GHG such as fossil CO₂ and CH₄, whereas GW impact is the more precise term when referring to TRACI.

4.16.2 Results

Table 12 shows the environmental performance of LSL manufacturing, both cumulative total as well as individual life-cycle stages (resource extraction (A1), transportation (A2), and product manufacturing (A3)).

The values in Table 12 are the cumulative impacts for the cradle-to-gate system boundary including forestry, transport, and product manufacturing. For example, the cradle-to-gate global warming (GW) impact was 274.9 kg CO₂eq/m³ of LSL produced and the major contribution was from resource extraction. The GW impacts from resource extraction, transportation, and product manufacturing were 153.12, 58.97, and 62.81 kg CO₂eq/m³ of LSL, respectively. Resin production contributed 124 kg/CO₂eq (45%). Overall, the contribution of the A1 stage (resource extraction, which included resin) was substantial or very high among all stages of the cradle-to-gate environmental impacts of LSL. The cradle-to-gate renewable and nonrenewable energy usages were 5,191 and 6,512 MJ/m³, respectively.

5. Interpretation

According to ISO 14040, the term life-cycle interpretation is the final phase of the LCA, and results of the LCI or LCIA, or both, are combined consistently and summarized as a basis for conclusions and recommendations with the defined goal and scope of the study. This phase in the LCA reports the significant issues based on the results of the LCI and LCIA of this report. Additional components report an

Table 11—Selected impact indicators, characterization models, and impact categories

Reporting category per tables E1–E5 in ISO 21930 (ISO 2017)	Indicator name	Abbreviation	Unit
Core Mandatory Impact Indicators	Global warming potential, fossil	GWP _{TRACI}	kg CO ₂ eq
Core Mandatory Impact Indicators	Global warming potential, w/ biogenic ^a	GWP _{BIO}	kg CO ₂ eq
Core Mandatory Impact Indicators	Depletion potential of the stratospheric ozone layer	ODP	kg CFC11eq
Core Mandatory Impact Indicators	Acidification potential of soil and water sources	AP	kg SO ₂ eq
Core Mandatory Impact Indicators	Eutrophication potential	EP	kg PO ₄ eq
Core Mandatory Impact Indicators	Formation potential of tropospheric ozone	SFP	kg O ₃ eq
Core Mandatory Impact Indicators	Abiotic depletion potential for fossil resources (ADP fossil)	ADP _f	MJ, NCV ^b
Core Mandatory Impact Indicators	Fossil fuel depletion	FFD	MJ surplus
Use of Primary Resources	Renewable primary energy carrier used as energy	RPRE	MJ, NCV
Use of Primary Resources	Renewable primary energy carrier used as material	RPRM	MJ, NCV
Use of Primary Resources	Nonrenewable primary energy carrier used as energy	NRPRE	MJ, NCV
Use of Primary Resources	Renewable primary energy carrier used as material	NRPRM	MJ, NCV
Secondary material, secondary fuel and recovered energy	Secondary material	SM	kg
Secondary material, secondary fuel and recovered energy	Renewable secondary fuel	RSF	MJ, NCV
Secondary material, secondary fuel and recovered energy	Nonrenewable secondary fuel	NRSF	MJ, NCV
Secondary material, secondary fuel and recovered energy	Recovered energy	RE	MJ, NCV
Mandatory Inventory Parameters	Consumption of freshwater resources	FW	m ³
Indicators Describing Waste	Hazardous waste disposed	HWD	kg
Indicators Describing Waste	Nonhazardous waste disposed	NHWD	kg
Indicators Describing Waste	High-level radioactive waste, conditioned, to final repository	HLRW	kg or m ³
Indicators Describing Waste	Intermediate- and low-level radioactive waste, conditioned, to final repository	ILLRW	kg or m ³
Indicators Describing Waste	Components for re-use	CRU	kg
Indicators Describing Waste	Materials for recycling	MR	kg
Indicators Describing Waste	Materials for energy recovery	MER	kg
Indicators Describing Waste	Recovered energy exported from the product system	EE	MJ, NCV
Additional Inventory Parameters for Transparency	Biogenic carbon removal from product	BCRP	kg CO ₂ eq
Additional Inventory Parameters for Transparency	Biogenic carbon emission from product	BCEP	kg CO ₂ eq
Additional Inventory Parameters for Transparency	Biogenic carbon removal from packaging	BCRK	kg CO ₂ eq
Additional Inventory Parameters for Transparency	Biogenic carbon emission from packaging	BCEK	kg CO ₂ eq
Additional Inventory Parameters for Transparency	Biogenic carbon emission from combustion of waste from renewable sources used in production processes	BCEW	kg CO ₂ eq
Additional Inventory Parameters for Transparency	carbon emissions from combustion of waste from nonrenewable sources used in production processes	CWNR	kg CO ₂ eq

^aISO 21930 requires a demonstration of forest sustainability to characterize carbon removals with a factor of –1 kg CO₂eq/kg CO₂. ISO 21930 Section 7.2.1 Note 2 states the following regarding demonstrating forest sustainability: “Other evidence such as national reporting under the United Nations Framework Convention on Climate Change (UNFCCC) can be used to identify forests with stable or increasing forest carbon stocks.” Canada’s UNFCCC annual report table 6-1 provides annual NET GHG Flux Estimates for different land use categories. This reporting indicates nondecreasing forest carbon stocks and thus the source forests meet the conditions for characterization of removals with a factor of –1 kg CO₂eq/kg CO₂.

^bNCV, net calorific value.

Table 12—Cradle-to-gate environmental performance of 1 m³ laminated strand lumber produced in North America (mass allocation) by value

Core mandatory impact indicator	Abbreviation	Unit	Total	A1	A2	A3
Global warming potential – TRACI 2.1	GWP _{TRACI}	kg CO ₂ eq	274.90	153.12	58.97	62.81
Global warming potential – w/ biogenic CO ₂	GWP _{BIO}	kg CO ₂ eq	274.90	–1,600.93	58.97	1,816.87
Depletion potential of the stratospheric ozone layer	ODP	kg CFC11eq	6.72E–06	1.22E–07	1.04E–07	6.50E–06
Acidification potential of soil and water sources	AP	kg SO ₂ eq	1.70E+00	9.02E–01	3.64E–01	4.33E–01
Eutrophication potential	EP	kg Neq	2.04E–01	8.41E–02	3.34E–02	8.63E–02
Formation potential of tropospheric ozone	SFP	kg O ₃ eq	39.51	17.92	10.68	10.90
Abiotic depletion potential for fossil resources	ADP _f	MJ, NCV ^a	4,015.88	2,667.58	737.86	610.44
Fossil fuel depletion	FFD	MJ surplus	597.92	394.44	110.79	92.69
Use of primary resources						
Renewable primary energy carrier used as energy	RPRE	MJ, NCV	5,190.65	25.43	1.69	5,163.53
Renewable primary energy carrier used as material	RPRM	MJ, NCV	13,063.02	13,063.02	0.00	0.00
Nonrenewable primary energy carrier used as energy	NRPRE	MJ, NCV	6,512.45	2,956.63	748.67	2,807.16
Nonrenewable primary energy carrier used as material	NRPRM	MJ, NCV	1,100.11	0	0	1,100.11
Mandatory inventory parameters						
Consumption of freshwater resources	FW	m ³	5.40	2.63	0.01	2.76
Indicators describing waste						
Hazardous waste disposed	HWD	kg	6.02E–01	5.54E–01	5.52E–05	4.72E–02
Nonhazardous waste disposed	NHWD	kg	2.96E+01	5.54E–01	5.52E–05	2.90E+01
High-level radioactive waste, conditioned, to final repository	HLRW	m ³	1.57E–05	0.00E+00	0.00E+00	1.57E–05
Intermediate- and low-level radioactive waste, conditioned, to final repository	ILLRW	m ³	2.34E–05	4.94E–08	5.69E–08	2.33E–05
Components for re-use	CRU	kg	0	0	0	0
Materials for recycling	MR	kg	0.47	0.00	0.00	0.47
Materials for energy recovery	MER	kg	0	0	0	0
Recovered energy exported from the product system	EE	MJ, NCV	0.000	0	0	0.000

^aNCV, net calorific value.

evaluation that considers completeness, sensitivity, and consistency checks of the LCI and LCIA results and conclusions, limitations, and recommendations.

5.1 Identification of Significant Issues

The objective is to structure the results from the LCI or LCIA phases to help determine the significant issues found in the results and presented in previous sections of this report. A contribution analysis was applied for the interpretation phase of this LCA study. A contribution analysis examines the contributions of life-cycle stages (A1, A2, and A3) or specific substances that contribute an impact.

5.2 Life-Cycle Phase Contribution Analysis

Table 13 shows the contributions of the three major life-cycle stages of LSL production. About 22.85% of GW impact (CO₂ equivalent emissions) came from the mill, that is, manufacturing of LSL (A3), and 55.70% and 21.45%

came from extraction (A1) and transportation (A2), respectively. The contribution of the A1 phase was substantial (mainly due to resin) and consistent among the core mandatory impact indicator categories.

Almost all of the renewable fuels were used in the A3 life-cycle stage (Tables 13 and 14). The A3 phase consumed about 68% of the total primary energy used in the manufacturing of LSL. This was because most of the heat, electricity, and fuels were used during the manufacturing process.

The first two phases, A1 (forest resource and resin) and A2 (feedstocks transport), consumed 25.5% and 6.4% of the total primary energy, respectively. About 32.5% of the total energy used in the A3 phase came from nonrenewable fossil and nuclear resources, and the rest came from renewable sources such as hydro, wind, solar, geothermal, and biomass. Around 99% of the energy used in the A1 and A2 phases came from nonrenewable resources (Table 14).

Table 13—Cradle-to-gate life-cycle impact assessment contribution analysis for three life-cycle stages of North American laminated strand lumber production (resource extraction (A1), transportation (A2), and manufacturing (A3))

	Abbreviation	Unit	Contribution (%)			
			Total	A1	A2	A3
Core mandatory impact indicator						
Global warming potential – TRACI 2.1	GWP _{TRACI}	kg CO ₂ eq	100	55.70	21.45	22.85
Depletion potential of the stratospheric ozone layer	ODP	kg CFC11eq	100	1.82	1.54	96.64
Acidification potential of soil and water sources	AP	kg SO ₂ eq	100	53.07	21.43	25.50
Eutrophication potential	EP	kg Neq	100	41.26	16.37	42.37
Formation potential of tropospheric ozone	SFP	kg O ₃ eq	100	45.37	27.04	27.59
Abiotic depletion potential for fossil resources	ADP _f	MJ, NCV ^a	100	66.43	18.37	15.20
Fossil fuel depletion	FFD	MJ surplus	100	65.97	18.53	15.50
Use of primary resources						
Renewable primary energy carrier used as energy	RPRE	MJ, NCV	100	0.49	0.03	99.48
Renewable primary energy carrier used as material	RPRM	MJ, NCV	100	100.00	0.00	0.00
Nonrenewable primary energy carrier used as energy	NRPRE	MJ, NCV	100	45.40	11.50	43.10
Nonrenewable primary energy carrier used as material	NRPRM	MJ, NCV	100	0.00	0.00	100.00
Mandatory inventory parameters						
Consumption of freshwater resources	FW	m ³	100	48.75	0.11	51.14
Indicators describing waste						
Hazardous waste disposed	HWD	kg	100	92.14	0.01	7.85
Nonhazardous waste disposed	NHWD	kg	100	1.87	0.00	98.13
High-level radioactive waste, conditioned, to final repository	HLRW	m ³	100	0.00	0.00	100.00
Intermediate- and low-level radioactive waste, conditioned, to final repository	ILLRW	m ³	100	0.21	0.24	99.55
Components for re-use	CRU	kg	—	—	—	—
Materials for recycling	MR	kg	100	0.00	0.00	100.00
Materials for energy recovery	MER	kg	—	—	—	—
Recovered energy exported from the product system	EE	MJ, NCV	—	—	—	—

^aNCV, net calorific value.**Table 14—Cradle-to-gate energy use contribution analysis of life-cycle phases of North American laminated strand lumber production (resource extraction (A1), transportation (A2), and manufacturing (A3))**

Sources of energy	Unit	Contribution (%)			
		Total	A1	A2	A3
Nonrenewable, fossil	MJ	34.32	89.47	98.34	7.66
Nonrenewable, nuclear	MJ	21.33	9.68	1.44	27.56
Nonrenewable, biomass	MJ	0.00	0.00	0.00	0.00
Renewable, biomass	MJ	41.40	0.30	0.05	60.67
Renewable, wind, solar, geothermal	MJ	0.70	0.01	0.05	1.02
Renewable, hydro	MJ	2.25	0.55	0.13	3.09
Total		100.00	100.00	100.00	100.00

Table 15—Cradle-to-gate energy use contribution analysis of sources of energy in each life-cycle phase of North American laminated strand lumber production (resource extraction (A1), transportation (A2), and manufacturing (A3))

Sources of energy	Unit	Contribution (%)			
		Total	A1	A2	A3
Nonrenewable, fossil	MJ	100.00	66.43	18.37	15.20
Nonrenewable, nuclear	MJ	100.00	11.56	0.43	88.01
Nonrenewable, biomass	MJ	100.00	0.27	0.14	99.59
Renewable, biomass	MJ	100.00	0.18	0.01	99.81
Renewable, wind, solar, geothermal	MJ	100.00	0.28	0.46	99.27
Renewable, hydro	MJ	100.00	6.20	0.37	93.44

Table 16—Uncertainty analysis of selected inventory results of North American laminated strand lumber production

Inventory parameter	Units	Standard deviation			
		Mean	deviation	Minimum	Maximum
Log transport distance: A2 input	t-km	626.52	240.94	263.98	745.85
Electricity: A3 input	kWh	276.01	2.88	274.58	280.34
Diesel: A3 input	L	2.48	0.02	2.45	2.49
Gasoline: A3 input	L	0.01	0.02	0.00	0.05
Natural gas: A3 input	m ³	0.40	0.26	0.00	0.53
Adhesive: A1 input	kg	30.82	1.53	28.51	31.57
Wood fuel: A3 input	kg	264.56	65.22	232.26	362.71

Table 15 shows the contribution of each category of energy resources among the three life-cycle phases of LSL production. Among the six categories of energy sources, most energy use was in LSL manufacturing.

5.3 Uncertainty Analysis

The uncertainty and sensitivity analyses aim to assess the reliability of the results. Some degree of uncertainty is present in the results because of the variation among different data providers. The uncertainty analysis investigates input data variations within the sample of production facilities. Statistics for key inventory results, such as electricity, diesel, natural gas, and wood fuel, are shown in Table 16. The standard deviation for each of these factors was calculated based on the sample data and was used to perform sensitivity analysis on these parameters.

In the sensitivity analysis, significant inventory parameters were altered to investigate the effect on the LCIA results. In this case, electricity, diesel, natural gas, and biomass fuel input were increased and decreased by 20%. The change in LCIA results is presented in Table 17. A 20% change in wood fuel, adhesive, and electricity used internally had significant effects on the results. For example, a 20% increase in wood fuel can increase GW, ozone depletion potential (ODP), and eutrophication potential (EP) by 2%,

7%, and 3%, respectively, with an expected spike in renewable primary energy carrier used as energy (RPRE) of nearly 28%. Variations in the use of other inputs, such as diesel and natural gas, did not have much impact on the results.

5.4 Completeness and Consistency Checks

The completeness and consistency checks help to establish and enhance confidence in the study. These improve the reliability of the results of the LCA study, including the significant issues identified in the interpretation.

The objective of the completeness check is to ensure that all relevant information and data needed for the interpretation are available and complete. Three selected information modules (“harvesting and forest management”, “resource and material transportation”, and “manufacturing of LSL”) were checked for data completeness including all elements such as raw and ancillary material input; energy input; transportation; water consumption; product and coproduct outputs; emissions to air; water and land; and waste disposal. All the input and output data were found to be complete, and no data gaps were identified.

The objective of the consistency check was to determine if the assumptions, methods, models, and data were consistent with the goal and scope of the study. Through a rigorous

Table 17—Sensitivity analysis (mass allocation)

Impact indicator	Unit	Baseline results	Log transport distance (%)				Electricity (%)		Diesel (%)		Natural gas (%)		Adhesive (%)		Wood fuel (%)	
			-20%	+20%	-20%	+20%	-20%	+20%	-20%	+20%	-20%	+20%	-20%	+20%	-20%	+20%
ODP	kg CFC11eq	6.72E-06	-0.31	0.31	-18.25	18.25	-0.04	0.04	0.00	0.00	0.00	0.00	-0.17	0.17	-6.34	7.31
GWP _{TRACI}	kg CO ₂ eq	274.91	-4.29	4.29	-2.37	2.37	-0.52	0.52	-0.07	0.07	-0.07	0.07	-9.03	9.03	-1.50	1.73
SFP	kg O ₃ eq	39.51	-5.41	5.41	-0.59	0.59	-1.53	1.53	-0.01	0.01	-0.01	0.01	-3.07	3.07	-1.82	2.10
AP	kg SO ₂ eq	1.70	-4.29	4.29	-1.21	1.21	-1.10	1.10	-0.01	0.01	-0.01	0.01	-6.00	6.00	-1.67	1.93
EP	kg Neq	2.04E-01	-3.27	3.27	-6.16	6.16	-0.71	0.71	-0.01	0.01	-0.01	0.01	-5.47	5.47	-2.79	3.22
FFD	MJ surplus	597.92	-3.71	3.71	-2.19	2.19	-0.48	0.48	-0.07	0.07	-0.07	0.07	-11.28	11.28	-1.01	1.17
ADPf	MJ, NCV ^a	4,015.92	-3.67	3.67	-2.12	2.12	-0.48	0.48	-0.06	0.06	-0.06	0.06	-11.38	11.38	-0.99	1.14
RPRE	MJ, NCV	5,190.65	-0.01	0.01	-1.40	1.40	0.00	0.00	0.00	0.00	0.00	0.00	-0.09	0.09	-23.86	27.51
NRPRE	MJ, NCV	6,512.49	-2.30	2.30	-8.03	8.03	-0.30	0.30	-0.04	0.04	-0.04	0.04	-7.89	7.89	-2.85	3.28

^aNCV, net calorific value.

process, consistency was ensured to fulfill the goal of the study in terms of assumptions, methods, models, and data quality including data source, accuracy, data age, time-related coverage, technology, and geographical coverage.

5.5 Limitations

This LCA was created using industry-average data for upstream materials. Variation can result from differences in supplier locations, manufacturing processes, manufacturing efficiency, and fuel type used. This LCA does not report all the environmental impacts caused by the manufacturing of the product but rather reports the environmental impacts for those categories within established LCA-based methods to track and report. Unreported environmental impacts include (but are not limited to) factors attributable to human health, land-use change, and habitat destruction. To assess the local impacts of product manufacturing, additional analysis is required.

This LCA report documents the results of a cradle-to-gate analysis and is not a comparative assertion, which is defined as an environmental claim regarding the superiority or equivalence of one product versus a competing product that performs the same function. This LCA does not make any statements that the product covered by the LCA is better or worse than any other product.

6 Treatment of Biogenic Carbon

Forests are understood as a natural system with multiple functions, the production function of timber being one of them. Therefore, natural growth and decay processes including natural disturbances, etc., are not attributable to the production function of forests and are therefore not considered in LCA. Harvesting operations lead to temporal decreases in forest carbon pools in the respective stand. Impacts on forest carbon pools resulting from the sustainable or unsustainable management of forests, however, cannot be defined or assessed on the stand level but require the consideration of carbon pool changes on the landscape level, that is, the level based on which management decisions are made. Resulting from the fundamental principle of sustainable forest management to preserve the production function of forests, total forest carbon pools can be considered stable (or increasing) under sustainable forest management. This is because temporal decreases of forest carbon pools resulting from harvesting on one site are compensated by increases of carbon pools on the other sites, forming together the forest area under sustainable forest management.

It is acknowledged that excessive extraction of slash, litter, or roots for bioenergy generation can lead to decreases in forest carbon pools. These activities, however, are not causally linked to the extraction of timber for the material use of wood. Effects on forest carbon pools related to the extraction of slash, litter, or roots are not attributable to the

material use of wood and are therefore not considered in this document.

To reflect the biogenic nature of wood, its renewability, and its potential carbon neutrality, the system boundary between nature and the product system under study is defined as follows:

- Wood entering the product system from nature accounts for the energy content and the biogenic carbon content as material inherent properties.
- All technical processes related to forestry operations intended to produce timber (e.g., stand establishment, tending, thinning(s), harvesting, and establishment and maintenance of forest roads) are considered within the system boundary and are subject to coproduct allocations as outlined in the reference PCR (ULE 2019).
- Human-induced impacts on forest carbon pools resulting in deforestation are not included. However, the forest inventory in the United States (Sahoo and others 2019) and Canada (FAO 2015) is either stable or increasing and managed sustainably.

Wood is a biobased material and thus contains biogenic carbon. Consideration of the biogenic carbon neutrality of wood is valid for North American wood products because national level inventory reporting shows overall increasing and/or neutral forest carbon stocks in recent years (FAO 2015, 2020; Oswalt and others 2019).

The accounting of biogenic carbon follows the requirements set out in ISO 21930 section 7.2.7 and 7.2.12. Per ISO 21930, biogenic carbon enters the product system (removal) as primary or secondary material. Carbon removal is considered a negative emission. The biogenic carbon leaves the system (emission) as a product or coproduct and directly to the atmosphere when combusted. These mass flows of biogenic carbon from and to nature are listed in the LCI and expressed in kg CO₂ [For example, 1 OD kg of wood equal to 0.5 kg carbon (assuming 50% carbon content) is equal to 1.83 kg of CO₂eq].

In the LCIA, the LCI flow of biogenic carbon removal is characterized with a factor of $-1 \text{ kg CO}_2\text{eq/kg CO}_2$ of biogenic carbon in the calculation of the GW impact [ISO 21930 requires a demonstration of forest sustainability to characterize carbon removals with a factor of $-1 \text{ kg CO}_2\text{eq/kg CO}_2$. ISO 21930 Section 7.2.7 Note 2 states the following regarding demonstrating forest sustainability: “Other evidence such as national reporting under the United Nations Framework Convention on Climate Change (UNFCCC) can be used to identify forests with stable or increasing forest carbon stocks.” Canada’s UNFCCC annual report table 6-1 provides annual net greenhouse gas (GHG) flux estimates for different land use categories. This reporting indicates nondecreasing forest carbon stocks, and thus the source forests meet the conditions for characterization of removals with a factor of

–1 kg CO₂eq/kg CO₂]. Likewise, the LCI flow of biogenic carbon emission is characterized with a factor of +1 kg CO₂eq/kg CO₂ of biogenic carbon in the calculation of the GW impact. Emissions other than CO₂ associated with biomass combustion (for example, methane or nitrogen oxides) are characterized by their specific radiative forcing factors in the calculation of the GW impact.

The ULE PCR specifies TRACI as the default LCIA method for GW. The TRACI method does not account for the removals or emissions of biogenic CO₂. We have thus manually calculated the component of the global warming potential (GWP) related to biogenic carbon separately. We have reported the GWP indicator both with and without the biogenic CO₂ component for maximum transparency.

The results for GW impact and biogenic CO₂ are as follows:

- GWP_{TRACI}: includes GHG emissions from the combustion of fossil resources and GHG emissions other than CO₂ from the combustion of biogenic resources (TRACI method)
- GWP_{BIO}: adds the net emissions of biogenic carbon to the GWP (TRACI method + net biogenic carbon)
- LCI flows of biogenic carbon emissions and removals (Table 18)

Following ISO 21930, emission from packaging (BCEK) is reported in A5 and emission from the main product is reported in C3/C4 end-of-life modules. The system boundary for this LCA only includes modules A1 to A3. About –1,754.05 kg CO₂eq (A1) was removed in the production of 1 m³ of LSL (Table 18). That same 1 m³ of LSL stores 312.6 kg of carbon or +1,145.88 kg CO₂eq (C3/C4). The coproducts produced during LSL production account for an additional +123.14 kg CO₂eq (A3) for a total “emission” in wood products leaving the system boundary of +1,269.02 kg CO₂eq. In summary, total removals were –1,754.05 kg CO₂eq, which was close to the total “emissions” from cradle-to-gate (A1 to A3) (Table 18).

7 Discussion

The goal of this study was to perform a cradle-to-gate LCA and estimate the environmental impacts of manufacturing LSL in North America using the data for the year 2019.

Table 19 shows the comparison between the previous study by CORRIM (2015) and this study. Compared with the previous study, the LCA results in this study showed substantial improvement or reduction in environmental impacts except for EP. In this study, there was a substantial decrease in some of the environmental impacts especially GW, smog, and energy used compared with the previous study (CORRIM 2015). Overall, there was an 8% decrease in the total primary energy use in the production of LSL in this study (12,031 MJ/m³) compared with the previous study (13,044 MJ/m³) by CORRIM (2015).

The differences in the environmental impacts between this study and the previous study (CORRIM 2015) can be attributed to two major factors: (i) differences in method (CED method) to estimate energy usage, mass-balance, and product density, and (ii) change in the use of electricity and heat and transport activities, especially truck transport. The previous study considered the HHV of fuels, whereas this study used lower heating value (LHV) to estimate total primary energy use in the production of LSL. The main product, LSL, carried 55% of total mass feedstocks in the previous study compared with 65% in this study.

8 Conclusions

The LCA considered three life-cycle phases: resource extraction including forest management and harvesting, wood residues production, and construction waste production (A1), transportation of all inputs (A2), and manufacturing of LSL (A3). This study included the LCI of forest resources, which relied on secondary and tertiary data. The LCI of manufacturing relied on primary survey data and secondary data for process inputs such as resin, natural gas, diesel, and electricity. The survey results were representative of operations in the North American regions that produce LSL. The survey data in this study represented 100% of the total production (333,780 m³) of LSL in North America for the year 2019.

The environmental impacts from the resource extraction (A1) and its transportation (A2) were very small compared with those from manufacturing (A3) of LSL production. Emissions to land and water were small and negligible. About 68% of the primary energy was used in the manufacturing of LSL compared with the rest of the life-

Table 18—Biogenic carbon inventory parameters

Additional inventory parameters	Unit	Total	A1	A2	A3	A5	C3/C4
Biogenic carbon removal from product, BCRP	kg CO ₂	–1,754.05	–1,754.05	—	—	—	—
Biogenic carbon emission from products (including residues), BCEP	kg CO ₂	1,269.02	—	—	123.14	—	1,145.88
Biogenic carbon removal from packaging, BCRK	kg CO ₂	–1.00	—	—	–1.00	—	—
Biogenic carbon emission from packaging, BCEK	kg CO ₂	0.16	—	—	—	0.16	—
Biogenic carbon emission from biomass boiler (internal heat), BCEW	kg CO ₂	485.03	—	—	485.03	—	—

Table 19—Life-cycle impact assessment comparison between the previous study (CORRIM 2015) (based on 2013 industry surveys) and current study (based on 2019 industry surveys) on laminated strand lumber (LSL) production in North America, mass allocation.

Impact category	Unit	Current study based on 2019 production data	Previous study based on 2013 production data	Change (%)
Ozone depletion potential	kg CFC11eq	6.72E-06	3.41E-06	97
Global warming potential, fossil	kg CO ₂ eq	274.90	294.51	-7
Eutrophication potential	kg Neq	1.70E-01	6.72E-02	203
Smog potential	kg O ₃ eq	39.51	32.22	23
Nonrenewable fossil and nuclear	MJ	6,512.45 ^a (6,838.02 ^b)	5,797.92 ^b	18 ^b
Renewables (solar, wind, hydro, geothermal, and biomass)	MJ	5,190.65 ^a (5,192.70 ^b)	7,245.69 ^b	-28 ^b
Freshwater (in LSL mill)	L	205.43	172.73	19

^aLower heating values of fuels.^bHigher heating values of fuels.

cycle stages. Similarly, most environmental impacts were from the manufacturing stage of LSL. This study estimated a decrease in environmental impacts (especially GW and energy use) compared with the previous study (CORRIM 2015). The amount of carbon stored in LSL was about five times the total cradle-to-gate GW impact.

9 Critical Review

9.1 Internal Review

The purpose of the internal review of an LCA report is to check for errors and conformance with the PCR before submittal for external review. This LCA is a product of work done by the USDA Forest Service, Forest Products Laboratory (FPL), following its agreement with the American Wood Council (AWC). The technical and editorial comments of the reviewers were carefully considered and, in most instances, incorporated into the final document. The FPL staff addressed the internal review comments, as appropriate, and maintains a record of all comments and responses for future reference.

The internal review of this document was performed by Dr. Maureen Puettmann, Director of Operations, The Consortium for Research on Renewable Industrial Materials (CORRIM), and James Salazar, Coldstream Consulting, Ltd.

9.2 External Review

The external review process is intended to ensure consistency between the completed LCA and the principles and requirements of the international standards on LCA (ISO 14040) and the product category rules for North American structural and architectural wood products (ULE 2018, 2019). Following FPL's internal review evaluation, documents were submitted to UL Environment (UL) for independent external review. The independent external review performed by UL was conducted by Thomas Gloria,

Ph.D., Industrial Ecology Consultants. After internal reviews and necessary revisions by addressing reviewers' comments and suggestions, documents were submitted to Underwriters Laboratories Environment (ULE) for independent external review. The independent external review performed by ULE was conducted by Grant R. Martin, LEED Green Associate, Environmental Project Manager, UL Environment & Sustainability, UL Verification Services, Inc., 2211 Newmarket Parkway, Suite 106, Marietta, GA 30067 USA. T: 678-872-0300 Ext. 14100, W: UL.com/environment.

10. Units and Conversions

Conversion factors for the units used in the LCA in this report are given in Table 20.

Table 20—Wood conversion in developing the life-cycle inventory for laminated strand lumber

To convert from	to	multiply by
Cubic feet (ft ³)	Cubic meters (m ³)	0.02831685
Pounds (avdp) (lb)	Kilograms (kg)	0.4535924
Cubic inches (in ³)	Cubic centimeters (cm ³)	16.393
Btus	Joules (J)	1,054
Cubic yards (yd ³)	Cubic meters (m ³)	0.7645549
Feet (ft)	Meters (m)	0.305
Gallons (U.S.) (gal)	Liters (L)	3.785
Kilowatt-hours (kWh)	Megajoules (MJ)	3.6
Miles (mi)	Kilometers (km)	1.609
Ounces (avdp) (oz)	Kilograms (kg)	0.028
Square feet (ft ²)	Square meters (m ²)	0.093
Tons (short)	Kilograms (kg)	907.185
Tons (short)	Metric tons (t)	0.9071847
Pounds (lb)	Metric tons (t)	0.0004
Watts (W)	Joules/second (J/s)	1
Yards (yd)	Meters (m)	0.914
Acres (a)	Hectares (ha)	0.405

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12 Appendix A—Laminated Strand Lumber Mill Survey

Introduction

Confidential

USDA FS Forest Products Laboratory/North American Laminated Strand Lumber (LSL) Survey-2020

This survey was sent to you as part of a larger collaboration between the USDA FS Forest Products Laboratory, American Wood Council (AWC), and The U.S. Endowment for Forestry and Communities, Inc.

Questions will be concentrated on annual production, electricity production, and usage, fuel use, material flows, and environmental emissions (i.e., emission data). We realize that you may not have all the information requested, especially when it comes to specific equipment/processing groups or what we call ‘machine centers’. The data you are able to provide will be appreciated.

Your data will be confidential; only weight-averaged values for the whole industry will be reported.

Our objective is to use the life-cycle information developed from this project to help develop the Business-to-Business Environmental Product Declaration for US building materials.

Company Name:

Facility Site (city, state):

Should we have a follow-up question about the data, please provide the name and the following information for the contact in your company.

Name:

Title:

Telephone:

Email:

Please send the completed survey to the following email or address by **April 20, 2020**. In addition, if you have questions about the survey, contact Kamalakanta Sahoo at the listed phone/email. Email is preferred.

Kamalakanta
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Yes	No	Equipment in mill
Log storage		
☐	☐	Dry deck
☐	☐	Sprinkled deck
☐	☐	Heated Pond
Log handling		
☐	☐	Log sorter/merchandizer
☐	☐	Debarker #
Ring, drum (circle one)		
Strands producing		
☐	☐	Strander #
☐	☐	Screens #
☐	☐	Bins #
Drying and screening		
☐	☐	Drum dryer #
☐	☐	direct-fired
☐	☐	indirect-fired
☐	☐	Bins #
☐	☐	Screens #
Bleding, forming, and pressing		
☐	☐	Blenders #
☐	☐	Forming machine(s) #
width: 4', 8', 12' (circle one)		
☐	☐	Pressing machine (s)
Hot pressing #		

Yes	No	Equipment in mill
Boiler		
☐	☐	Wood-fired boiler(s) #
		#1 size mmbtu/hr
		#2 size mmbtu/hr
☐	☐	Natural gas-fired boiler
		size mmbtu/hr
☐	☐	Oil-fired boiler
		size mmbtu/hr
☐	☐	Emission control device(s)
		Cyclones #
		Bag-houses #
		Electrified filter bed (EFB) #
☐	☐	Cogeneration facility (electricity)
Finishing		
☐	☐	Trimmer(s) #
☐	☐	Sander(s) #
Packaging		
☐	☐	Plastic wrapping (bags)
☐	☐	Metal strapping
☐	☐	Plastic strapping

Annual materials inputs

Woody resources inputs [Please provide wood inputs processed at your facility]

MFBM: thousand board feet

Name, Dimensions			Mode of Transportation									
			Annual Quantity	Unit	Moisture Content	Approx. Transport	% truck	% rail	% water	Log scale	Diameter	Unit
Logs (wood species)												
e.g. Douglas fir			10000	MFBM	45 %	200 mi	30 %	70 %	0 %	Doyle		10 in
Yellow poplar				MFBM	%	mi	%	%	%			
Aspen				MFBM	%	mi	%	%	%			
Yellow birch				MFBM	%	mi	%	%	%			
Hard maple				MFBM	%	mi	%	%	%			
Soft maple				MFBM	%	mi	%	%	%			
add others					%	mi	%	%	%			
					%	mi	%	%	%			
					%	mi	%	%	%			

Ancilliary materials inputs [Please provide the material inputs (other than wood) directly as part of the product]

Name	Moisture Content			Mode of Transportation				
	Annual Quantity	Unit	Moisture Content	Approx. Transport	% truck	% rail	% water	
e.g. Resins	10000	lbs	30 %	500 mi	30 %	70 %	0 %	
Slack wax			%	mi	%	%	%	
Adhesive (e.g., MDI)			%	mi	%	%	%	
			%	mi	%	%	%	
			%	mi	%	%	%	
			%	mi	%	%	%	
			%	mi	%	%	%	

Machinery ancilliary materials inputs

Mode of Transportation		
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Name	Annual Quantity	Unit	Approx. Transport	% truck	% rail	% water
Sealant			mi	%	%	%
Release agent			mi	%	%	%
Motor oil			mi	%	%	%
Greases			mi	%	%	%
Hydraulic fluid			mi	%	%	%
Antifreeze			mi	%	%	%
Lubricating fluid			mi	%	%	%
add others			mi	%	%	%

Packaging materials inputs

Name	Annual Quantity	Unit	Mode of Transportation		
			Approx. Distance to	% truck	% rail % water

Steel strapping			mi	%	%	%
Plastic strapping			mi	%	%	%
Cardboard strap protectors			mi	%	%	%
Plastic packaging			mi	%	%	%
Wooden spacers			mi	%	%	%
add others			mi	%	%	%

Water inputs

Water	Annual volume	Unit	Source ¹	Application ²	% Recycled	Waste water treatment ³
Fresh water						
add other						

¹Source: e.g. municipal supply, private well, river, lake, etc.

²e.g. boiler/co-generation water , yard spraying, adhesive mixing, etc.

³Provide information on the waste water treatment

Annual energy and fuel inputs

Name	Annual Quantity	Unit
Heat and electricity		
Steam (Purchased)		
Steam (Self-generated)		
Electricity (Purchased)		
Electricity (Self-generated)		
Fuels		
Diesel		
Gasoline		
Natural gas		
Propane		
Ligth fuel oil		
Heavy fuel oil		
Wood fuel*		

***Details on wood fuel inputs**

*Details on wood fuel inputs				Mode of Transportation				
Name	Annual Quantity	Unit	Moisture Content (wet basis)	Approx. Distance (Mill to suppliers)	Unit	% truck	% rail	% water
Purchased woodfuel								
Hog fuel (green)			%		mi	%	%	%
Hog fuel (dry)			%		mi	%	%	%
add other			%		mi	%	%	%
			%		mi	%	%	%
Self-generated (in-house) woodfuel								
Bark (green)			%					
Short strands (green)			%					
Short strands (dry)			%					
Wood residue (with resin)			%					
Bag-house particulate			%					

Mention self-generated heat and electricity using woodfuel

Name	Total Produced	Unit	Used (In-house)	Sold (outside of mill)
Heat (Wood boiler)			%	%
Electricity (co-generation*)			%	%
Heat (co-generation*)			%	%

*Mention the amount (% of total) of heat and electricity generated using wood fuel used in mill and sold to outside of the mill)

Outputs: Products and Co-products

Please indicate every commercial product output

Main product output

Name	Annual Quantity	Unit	Moisture Content	Density	Unit	Grade/Notes
Aggregate (All dimensions)						
e.g., laminated strand lumber	100000	cubic meter	%	600 kg/m ³		
e.g., oriented strandboard	200	cubic meter	%	800 kg/m ³		
			%			
			%			

Mentioned detailed dimensions	Annual Quantity	Unit	Moisture Content	Density	Unit	Grade/Notes	End sealed (Y/N)
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Individual LSL dimensions

for example: Thickness x Width (1/2" x 3-1/2")	2000	cubic meter	10 %	750 kg/m ³			Y
			%				
			%				
			%				
			%				
			%				
			%				

Note: add more rows if necessary

Coproduct Output: Woody

Name	Annual Quantity	Unit	Moisture Content	Grade/Notes
for example: Bark	5000	tons	50 %	mc in wet basis
OSB flakes, sold				
OSB flakes, to OSB				
Bark				
Screens remaining (green)				
Screens remaining (dry)				
Cutting remaining				

Note: Include the wood fuel used for the heat and co-generation. If you don't have individual values then explain them clearly

Coproduct Output: Heat and Electricity

Name	Annual Quantity	Unit	Note
Electricity			
Steam			

Annual solid waste generated

Name	Annual Quantity	Unit	Disposal Methods				Mode of Transportation			
			Incineration with Energy Recovery	Composting	Landfilling	Other	Distance to disposal	% truck	% rail	% water
Wood waste ¹			%	%	%	%	mi	%	%	%
Boiler ash			%	%	%	%	mi	%	%	%
Recycled metals			%	%	%	%	mi	%	%	%
Pastic strapping			%	%	%	%	mi	%	%	%
Cardboard			%	%	%	%	mi	%	%	%
Wrapping paper			%	%	%	%	mi	%	%	%
add other			%	%	%	%	mi	%	%	%
			%	%	%	%	mi	%	%	%

¹Only include the wood waste disposed (exclude the woodfuel used in-house and sold to outside)

Annual air and water emissions from mill including co-generation

Reported Year:

Air emissions			Water emissions		
Name	Annual Quantity	Unit	Name	Annual Quantity	Unit
Particulates*			Fluorides		
Nitrogen Oxides			Dissolved Solids		
Hydrocarbons			BOD		
Sulfur Oxides			COD		
Carbon Monoxide			Phenol		
Aldehydes			Sulfides		
Other Organics			Oil		
Methane			Suspended Solids		
VOCs			Acid		
Acetaldehyde			Metal Ion		
Acrolein			Cyanide		
Formaldehyde			Chromium		
Methanol			Iron		
Phenol			Aluminum		
HAPS (other)			Nickel		
Odororous Sulfur			Mercury		
Ammonia			Lead		
Hydrogen Fluoride			Phosphates		
Lead			Zinc		
Mercury			Ammonia		
Chlorine			add other		
add other					

Indicate whether reported emissions include boiler emissions that cannot be separated out from other mill process emissions:

Describe size distribution of particulates if known. i.e. %PM10, %<PM10, %PM2.5, %<PM2.5

Emission Controls

Describe any emission control equipment in place (bag house, cyclone, multi-cyclone, etc)

Describe on-site wastewater treatment, if any. Also, if discharging to treatment plant, please indicate.

Toxics Release Inventory (TRI)

What is the TRI ID Number for your mill/facility?