Cradle to Gate Life Cycle Assessment of Glue-Laminated Timbers Production from the Southeast

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1 Background

CORRIM, the Consortium for Research on Renewable Industrial Materials, has derived life cycle inventory (LCI) for major wood products and wood production regions in the United States. The life cycle inventory data start with forest regeneration and end with final product at the mill gate. Research has covered nine major forest products including both structural and nonstructural uses and four major regions: in this report we focus on glue-laminated timbers produced in the US southeast (SE) region. The SE regional data is a representative cross-section of forest growth and manufacturing processes in Alabama, Arkansas, Florida, Georgia, Louisiana, Mississippi, and Texas. This document updates the current plywood LCI's from a gate to gate to a cradle to gate LCI. Updates include the addition of SE forestry operations, boiler, resin, and electrical grid data that have been developed since the original mill surveys were conducted during 1999 and 2000. The updated LCI data were used to conduct life cycle impact assessments (LCIA) using the North American impact method, TRACI 2 v4 (Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts) (Bare et al. 2011). These updates are necessary for the development of environmental product declarations (EPD) which will be based on this document. This document originates from the CORRIM LCI reports by Puettmann and Wilson (2004, 2005) and Johnson et al. (2005). Updates in this report from the original Puettmann and Wilson report include: wood combustion boiler updates, North American resin data (Wilson 2009), electricity grid updates, with results expressed per unit of final product (1 m^3 glue-laminated timbers), and a LCIA. Updates to the forestry operations report include electricity grid updates and a LCIA using the TRACI method. This report follows data and reporting requirements as outlined in the Product Category Rules (PCR) for North American Structural and Architectural Wood Products (PCR 2011) that will provide the guidance for preparation of North American wood product EPD.

2 Introduction

The goal of this work is to determine energy and material inputs and outputs associated with the production of glue-laminated timber from the manufacturing base located in the SE region of North America. These data are needed for the inclusion of the production process in life-cycle analyses of wood. The data were obtained through a scientifically sound and consistent process established by the Consortium for Research on Renewable Industrial Materials (CORRIM), following ISO14040 standards (ISO 2006).

The scope of this study includes cradle-to-gate LCIs based on primary data for producing glue-laminated timber from softwood lumber using practices and technology common to the SE region. Lumber production was obtained from Milota et al. (2005) and Puettmann et al. (2012) reports. Logs for lumber production are obtained from the forest resource base located in Georgia, Alabama, Mississippi, and Louisiana as representative of the southern pine region. Data for the life cycle assessment (LCA) are based on manufacturing gate to gate LCI's from CORRIM reports (Puettmann and Wilson 2004) and forest resources cradle to gate LCI's specific to the region (Johnson et al. 2005). The report does not consider the impact of how the wood was used which requires a comparison to the impact of substitute products.

3 Description of Product

Structural glue-laminated (Glulam) timbers are one of the oldest glued engineered wood products dating back to the late 1800s. Glulam is an engineered, stress-rated product that consists of two or more layers of lumber that are glued together with the grain of all layers, which are referred to as laminations, parallel to the length. Glulam is defined as a material that is made from suitably selected and prepared pieces of wood either in a straight or curved form, with the grain of all pieces essentially parallel to the longitudinal axis of the member (Figure 1). The maximum lamination thickness permitted is 50 mm (2 in.), and the laminations are typically made of standard 25- or 50-mm- (nominal 1- or 2-in.-) thick lumber. North American standards require that glulam be manufactured in an approved manufacturing plant. Because the lumber is joined end to end, edge to edge, and face to face, the size of glulam is limited only by the capabilities of the manufacturing plant and the transportation system.

Figure 1 Glue-laminated beams.

Glulam beams are used as concealed or exposed structural beams and columns in residential and commercial construction, warehouse roof beams and purlins, church arches, and girders and deck panels for timber bridges. Glulam timbers come in a variety of sizes with production based on volume basis, typically board feet (1 board foot = 0.0024 m^3), and sold by retailers on a linear basis. Approximately 60% of glulam produced in the United States is used in domestic new residential and remodeling construction (Adair 2002). The next largest segment is the nonresidential market representing 31%. The remainder of production is sold into industrial (4%) and export (5%) markets. Glulam timbers can be made from any wood species provided its mechanical and physical properties are suitable and it can be properly glued. In the SE region it is made from southern pine species including longleaf (*Pinus. Palustris* Mill.), shortleaf (*P. echinata* Mill), loblolly (*P. taeda* L.*),* and Slash (*P. elliottii* Engelm.) pine.

All lumber used in glulam production and produced from the softwood lumber process is purchased as lamstock. Lamstock is defined as a special grade of lumber used in constructing laminated timbers. The lamstock lumber sizes produced in the SE are shown in Table 1.

Table 1 Lamstock sizes used in production of Glued-Laminated Timbers, SE.

Lamstock sizes for glulam (actual)				Percent
Width	Depth	Width	Depth	
mm		inch		
44.45	149.35	1.75	5.88	65
44.45	196.85	1.75	7.75	35

3.1 Functional and declared unit

In accordance with the PCR (2011), the declared unit for glulam is one cubic meter (1.0 m^3). A declared unit is used in instances where the function and the reference scenario for the whole life cycle of a wood building product cannot be stated (PCR 2011). For conversion of units from the US industry measure, 1.0 board foot = 0.0024 m^3. All input and output data were allocated to the declared unit of product based on the mass of products and co-products in accordance with International Organization for Standardization (ISO) protocol (ISO 2006).

3.2 System Boundaries

The system boundary begins with regeneration of forest in the southeast and ends with glulam timbers packaged to leave the mill gate (Figure 2). The forest resources system boundary includes: planting the seedlings, forest management which included site preparation, thinning, and fertilization on a subset of hectares, and final harvest. The transportation of logs from the woods to the mill is accounted for with the glulam manufacturing (Figure 2). Seedlings and the fertilizer and electricity it took to grow them were considered as inputs to the system boundary. The glulam complex was modeled with a single unit process. Lamstock inputs were models consistent with Puettmann et al. (2012) (Figure 2). Outputs to the system boundary include 1 m^3 of glulam ready to be shipped, air and water emissions, solid waste and small volumes of co-products (shavings, trimmings, and sawdust). The co-products are no longer tracked once they leave the system boundary.

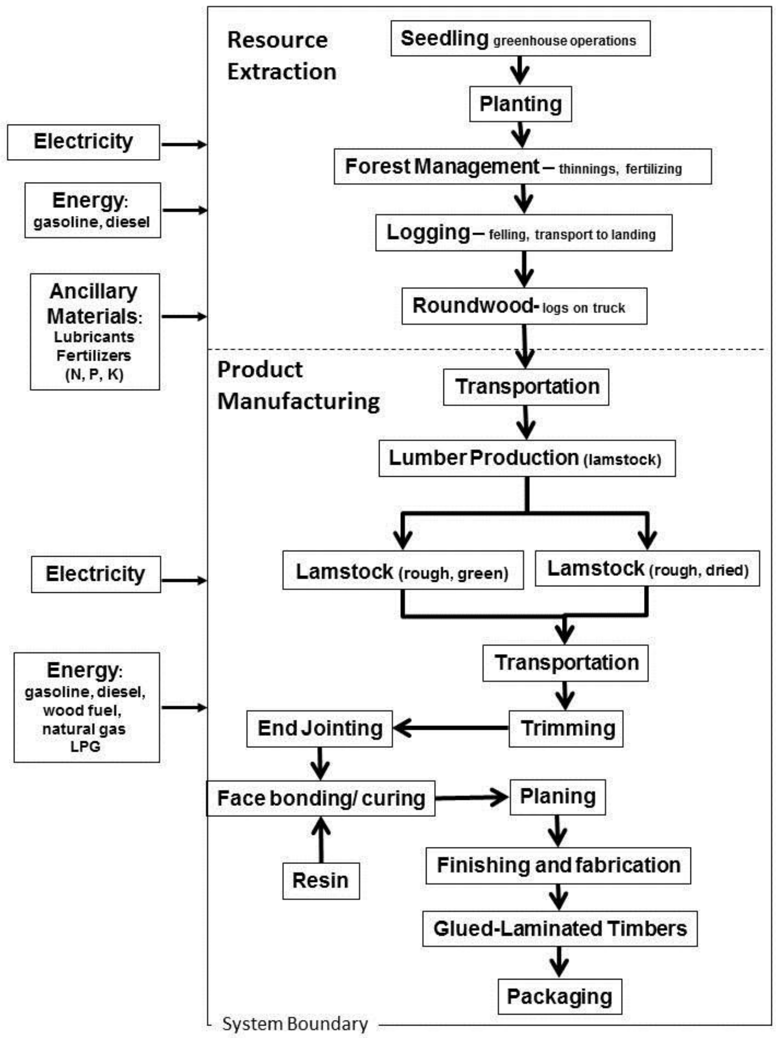

Figure 2 Cradle to gate life cycle stages for Glue-Laminated Timbers, SE.

3.3 Description of data/Process Description

3.3.1 Forestry Operations

Forestry operations include growing seedlings, site preparation, planting, fertilization (where applicable) and final harvest. The specific processes involved are reforestation: which includes seedling production, site preparation, planting, and fertilization, and harvesting: which includes felling, skidding, processing, and loading for both commercial thinning and final harvest operations. Weighted average allocation to different processes takes into account inherent differences in site productivity and energy usage by different kinds of logging equipment. Inputs to the forest resources management LCI include seed, electricity used during greenhouse operations, fertilizer used during seedling production and stand growth, and the fuel and lubricants needed to power and maintain equipment for site preparation, fertilization, and harvest operations. The primary output product for this analysis is a log destined for the plywood mill. The co-product, non-merchantable slash, is generally left at a landing and disposed of through mechanical activities or prescribed fire.

Logs used in the production of softwood lumber in the SE include in their life cycle the upstream activities associated with establishment, growth, and harvest of trees (Figure 2). This group of activities is collectively referred to as forest resource management. The forest resource management life cycle stages includes the efforts required to establish a forest stand, to treat that stand through to maturity, and to harvest the merchantable logs from the stand. Stand establishment involves preparation of the site for planting and planting of seedlings on the prepared site. Intermediate stand treatments enhance growth and productivity while the stand is growing and can involve thinning, fertilization, or both. In the SE, 68% of stands have some level of fertilizer applied, with the area treated determined by management intensity.

In the SE most harvested volume comes from forest operations on private lands where investment in timber is the precursor to harvest. Harvested lands are reforested for the next crop cycle with the sequence of treatments from planting to harvest averaging 27 years. Forestry operations and their associated impacts are not stationary and will change based on both past and prospective technologies, evolving forest management procedures, and market demands. Given that the nature of productivity gains is not confirmed or well developed, this assessment was based on data representing the current state of the art in forest operations: it does not discount future operations or estimate potential productivity gains from future technologies. Outputs representing quantities of product, measures of consumed resources, and the emissions associated with those consumed resources were developed as a weighted average across the hectares managed for timber production. These quantities of product are used as inputs to the wood product manufacturing LCI and the consumed resources and emissions are tracked for inclusion in the cradle to gate LCI.

The forest resource management LCI was structured from three general combinations of management intensity and site productivity. Scenarios developed for the Southeast represent a composite of stands from the extensive database managed by the Forest Nutrition Cooperative at North Carolina State University (Hafley et al 1982; Buford 1991). Management intensities ranged from little intervention on low site productivity lands that are often managed by Non-industrial Private Forest Landowners with a focus on other forest values, to higher management intensities involving combinations of fertilization and thinning on high productivity lands owned by industrial interests. Associated with each combination of management intensity and site productivity is an estimated yield of biomass based on forest growth and yield models. For the SE, growth and yield was based on models by Hafley et al. (1982) and Buford (1991).

3.3.1.1 Regeneration (seedling production and planting process)

Environmental burdens associated with the production of seedlings including fertilizer used in greenhouses or fields, and the electrical energy required to operate forest nursery pumps and to keep seedlings cool for planting were included as inputs to the regeneration process (Table 2). Greenhouse operations data for the SE were based on data from South and Zwolinski (1996). All seedlings in the SE were planted by hand. The only energy factors associated with planting were related to travel to and from the planting site.

Stand treatment options for the Southeast were developed by Lee Allen of the North Carolina Tree Nutrition Cooperative (Allen 2001). Based on that input, fertilization regimes were developed for the mid-intensity and high-intensity scenarios but not for the low-intensity option. Fertilization differences between the mid-and high-intensity options were primarily associated with the frequency of application. The high intensity option involved fertilization every four years over the 25-year life of the stand. The mid-intensity option involved fertilization at years two and sixteen. The fertilizer mixture included nitrogen, potassium, and phosphorus.

Table 2 Inputs to the regeneration phase and mid-rotation fertilization per hectare (ha) of forest.

		Low intensity	Medium intensity	High intensity	Weighted Average
		Reforesting 1 ha			
Diesel and Gasoline	L	38.55	132.27	272.21	104.59
Seedlings, at greenhouse	p[1]	1,794	1,794	1,794	1,794
Nitrogen in fertilizer					
In Seedlings	kg	0.14	0.14	0.14	0.14
On Site	kg	-	264.52	712.86	189.06
Phosphorous in fertilizer		-	-	-	-
In Seedlings	kg	0.01	0.01	0.01	0.01
On Site	kg	-	72.86	128.90	48.70
Potassium in fertilizer		-	-	-	-
In Seedlings	kg	0.08	0.08	0.08	.08
On Site	kg	-	-	-	-

[1] p = individual seedling

3.3.1.2 Equipment

Timber harvesting activities include four components: felling (severing the standing tree from the stump), processing (bucking, limbing and/or topping) which involves removal of non-merchantable limbs and tops and cutting of the tree into merchantable and transportable log lengths, secondary transportation (called skidding on gentle slopes and yarding on steep slopes),which is a transportation step that moves trees or logs from the point of felling to a loading point near a haul road, and loading (moving logs from the ground to haul vehicles). Although all functions are required to remove logs from the woods, the specific order and location of the operations will vary by harvesting system as cable yarding systems used in steep terrain have the processing step occur prior to the secondary transport step. Primary transportation is hauling logs from the woods to a manufacturing location and it is included in the LCI for the primary manufacturing facility.

This analysis is based on data for the most common mechanized harvesting system in use in the SE region. Mechanized felling utilizes a cutting device mounted on a woods tractor (feller-buncher) that travels through the stand to cut and bunch trees, transportation of those harvested trees to a landing (skidding), and the use of another machine that can delimb and process trees into logs at the landing. Two general systems were used. A smaller feller-buncher and grapple skidder and a larger, more capital-intensive system. The processing operation for this type of system generally takes place at the landing. Thus, whole trees are moved to the landing through the secondary transportation operation and are then processed into logs. Since whole trees are moved to the landing, the removed carbon from the site includes both the stem and the crown.

Variations in harvest equipment size affect machine productivity and therefore emissions per m^3 of logs produced. Harvest equipment operational efficiencies vary between thinning and final harvest (clearcut) which affects machine productivity and therefore emissions per m^3 of logs produced. To account for this, equipment usage was allocated between thinning operations and final harvest for those management regimes that use thinning (Table 3).

Table 3 Equipment allocation by treatment and management intensity

Management Intensity	Thinning	Final Harvest (usage per final volume harvested)
Low intensity site		
Medium Feller Buncher	NA	100%
Small Skidder	NA	100%
Slide Boom De-limber	NA	100%
Large Loader	NA	100%
Medium intensity		
Large Feller Buncher	26%	74%
Medium Crawler	26%	74%
Slide Boom De-limber	26%	74%
Large Loader	26%	74%
High intensity		
Large Feller Buncher	36%	64%
Medium Crawler	36%	64%
Slide Boom De-limber	36%	64%
Large Loader	36%	64%

3.3.1.3 Thinning and Final Harvest Process

A single estimate of the average volume harvested per unit area was developed by weighting three combinations of site productivity and management intensity based on the relative percentage of the land base they occupy which is given as percent area in management class in Table 4. Site productivity as measured by site index, the height of dominant trees at a base year, usually 25 or 50 years, and ownership class was obtained from the U.S. Forest Service Resource Planning Assessment database (USDA 2000, Mills 2001). A combination of these data and expert opinion was used to categorize the number of private forest hectares into the management intensity classes. The first class reflects non-industrial private forests (NIPF) with low-intensity management that might be implemented by the small private landowner. The second reflects high-intensity management on NIPF lands and/or low intensity management on industrial lands. The third scenario reflects high intensity management on industrial tree farms. Specific assumptions associated with these three scenarios are outlined in Table 4. In the Southeast, 37% of industrial and non-industrial private forestlands were classified in the lowest productivity class, 58% in the middle productivity class, and 5% in the highest class. The allocation of forested area to management intensity/site productivity class produces the expected log volume recovered from the forest resource as shown in Table 4. Allocating per ha values from Table 2 to the total yield of 236 m^3/ha is used to carry forward the environmental burdens of the reforestation effort on a per m^3 basis.

Table 4 Input assumptions for three levels of management intensity in the SE.

Management intensity class prescription	Low Intensity	Medium Intensity	High Intensity	Weighted Average
	per hectare			
Rotation Age - Years	30	25	25	27
Planting Density-Trees/hectare	1,794	1,794	1,794	1,794
Fertilization	None	Years 2,16	Years 2,5,9,13,17,21	
Commercial Thin 1st - m^3	0	63	59	39
at year		17	13	
Commercial Thin 2nd - m^3	0	0	58	3
at year			19	
Final Harvest - m^3	220	175	205	193
at year	30	25	25	
Total yield/hectare - m^3	220	238	323	236
Percent Thinned	0%	26%	36%	17%
Percent Sawlogs	38%	31%	52%	35%
Percent area in Class	37%	58%	5%	

Fuel consumption and energy use for forest resource management processes were averaged by the percent area in each class to develop weighted average values for the SE region by major process (Table 5).

Table 5 Fuel consumption for SE forest resource management processes (regeneration, thinning, and harvest).

	Unit	Fuel Consumption per m^3
Seedling, Site Prep, Plant, Pre-commercial Thinning		
Diesel and gasoline	L	0.515
Lubricants	L	0.009
Electricity	kWh	0.455
Commercial Thinning and Final Harvest		
Diesel	L	2.930
Lubricants	L	0.050
Total Forest Extraction Process		
Gasoline and Diesel	L	3.440
Lubricants	L	*0.054*
Electricity	kWh	0.455

3.3.2 Wood Product Manufacturing

3.3.2.1 Transportation Process

Logs are transported to lumber mills in the SE by truck (Table 6). Lamstock (lumber) is transported both green and dry, unplaned (rough) to glulam facilities. Glulam required two types of resin, one for finger jointing and one for bonding the lamstock. Packaging materials are also transported to the glulam facility as every timber is strapped and wrapped before shipping. All flow analyses of wood process were determined on an oven-dry weight specific gravity[1] of 0.56.

Table 6 Average delivery distance (one-way for materials to produce Glue-Laminated Timbers, SE.

Material delivered to mill	Delivery Distance	
	kilometers	miles
Logs to Lumber/Lamstock Production	92	57
Lamstock, green	0	0
Lamstock, dry	433	269
Resin (PRF and MUF)	689	428
Steel strapping - Packaging	1,219	757
Wrapping material - Packaging	1,843	1,145

3.3.2.2 Energy use and generation

A wood boiler was only used at the sawmill for lamstock production. No wood fuel was used directly in the manufacturing of SE glulam timbers (Table 7). The USLCI database was used for boiler processes inputting wood fuel (NREL 2012). This boiler process is based on the US Environmental Protection Agency (EPA) AP-42, Compilation of Air Pollutant Emission Factors (EPA 2006). The AP-42 emission factors assume no emission controls and therefore likely over-estimates the impact factors for wood emissions.

Table 7 Wood Boiler Process for Glulam production.

Product	Value	Unit/m^3
Wood biomass, combusted in industrial boiler	1.00	kg
Materials/fuels		
Wood fuel, purchased	1.00	kg
Emissions to air		
Acetaldehyde	7.47E-06	kg
Acrolein	3.60E-05	kg
Antimony	7.11E-08	kg
Arsenic	1.98E-07	kg
Benzene	3.78E-05	kg
Beryllium	9.90E-09	kg
Cadmium	3.69E-08	kg
Carbon dioxide, biogenic	1.76E+00	kg
Carbon monoxide	5.40E-03	kg
Chlorine	7.11E-06	kg
Chromium	1.89E-07	kg
Cobalt	5.85E-08	kg

[1] Green specific gravity uses oven dry mass and green volume of the wood resource.

Dioxin, 2,3,7,8 Tetrachlorodibenzo-p-	7.74E-14	kg
Formaldehyde	3.96E-05	kg
Hydrogen chloride	1.71E-04	kg
Lead	4.32E-07	kg
Manganese	1.44E-05	kg
Mercury	3.15E-08	kg
Metals, unspecified	3.85E-04	kg
Methane	1.89E-04	kg
Methane, dichloro-, HCC-30	2.61E-06	kg
Naphthalene	8.73E-07	kg
Nickel	2.97E-07	kg
Nitrogen oxides	1.17E-04	kg
Nitrogen oxides	1.98E-03	kg
Particulates, > 2.5 um, and < 10um	4.50E-03	kg
Phenols, unspecified	4.59E-07	kg
Selenium	2.52E-08	kg
Sulfur oxides	2.25E-04	kg
TOC, Total Organic Carbon	3.68E-05	kg

Electricity was used in all steps in glulam production. Electricity was consumed by the debarker, bucker, saws, pneumatic and mechanical conveying equipment, fans, hydraulic pumps, saws, and a radio-frequency drier. Diesel fuel use is attributed to onsite loaders. Forklifts and onsite trucks used small amounts of LPG and gasoline, respectively.

3.3.2.3 Softwood Lumber Production

Lamstock is produced in the SE at softwood lumber sawmills (Milota 2004, Puettmann et al. 2012). Lamstock lumber production includes debarking the logs, sawing green lumber, and drying lumber. The lumber/lamstock is transported unplaned (rough) dry to glulam production facilities. The softwood lumber production process was a multi-stage process producing both green and dry rough lumber. Details on this process are found in the Puettmann et al. 2012 LCA report. Inputs are logs with bark. Outputs are rough green lumber and rough dry lumber.

3.3.2.4 Phenol resorcinol formaldehyde resin

Phenol-resorcinol-formaldehyde (PRF) resin is used for face bonding the lamstock layers together. The PRF data was collected by survey from 8 plants in U.S. that represented 63 percent of total production for the year 2005 (Wilson 2009). Total annual production of PRF was 15,513,000 kg (34,166,667 lb) of neat[2] resin at 60 percent non-volatile solids content. PRF resins differ somewhat from the other resins in that hardeners are required to help in curing glue laminated timbers and I-joists. PRF resin can be cold or hot cured, and can be radio-frequency cured.

3.3.2.5 Melamine urea formaldehyde resin

Melamine-urea-formaldehyde (MUF) resin is used for finger jointing in glulam production. MUF production data was collected by survey from 6 plants in U.S. that represented 77 percent of total production for the year 2005 (Wilson 2009). Total annual production was 86,588,000 kg (190,893,000 lb) of neat resin at 60 percent non-volatile solids content. MUF production is essentially identical to the production of urea formaldehyde resin (these resins are used for particle board and medium density fiberboards) with the exception that melamine, about 8 percent by weight on a neat resin basis, is substituted for a portion of the urea input. The inputs to produce 1.0 kg of neat MUF resin at 60 percent non-volatile solids content consist of three primary chemicals on a dry basis of melamine at 0.081 kg,

[2] Neat resin means the resin as purchased from the supplier, does not include any inert fillers.

urea at 0.397 kg and methanol at 0.304 kg, much lesser amounts of formic acid, ammonium sulfate, and sodium hydroxide, and 0.791 kg of water. A significant portion of the processing water is recycled back into the resin.

3.3.2.6 Radio Frequency Driers

Glulam production plants use both radio frequency drying and cold curing processes to cure the resin for face bonding. Radio frequency drying is used exclusively for finger jointing with MUF resins. The surveys indicated both radio frequency (47%) and cold cure (53%) processes used in SE glulam production. In radio frequency drying, material is exposed to an electronic field that alternates about 40,000,000 times per second. When the field alternates, the water molecules in the material also alternate. The resulting friction causes the water to heat uniformly throughout the product. Radio frequency drying can save energy because only the product itself is heated. Another benefit is that no equipment warm up or cool down is necessary. The technology typically replaces process steam heat.

3.3.2.7 Glue-laminated beam process

The manufacturing process involves drying green lumber, grading lumber, and end jointing the lumber into longer laminations. End jointing is also referred to as finger-jointing. Once the lumber is finger jointed, the next steps are face bonding the laminations together with resin, finishing and fabrication. The major material inputs are lamstock (green and/or dry), and resins. Very little emissions are generated by the glulam manufacturing. Co-products produced are a mix of sawdust, trimmings, and shavings. Co-products account for only 18 percent by mass of the output. Both phenol resorcinol formaldehyde (PRF) and melamine urea formaldehyde (MUF) resins are used in glulam production. For end jointing, MUF is the most common resin used while PRF is primarily used for face bonding. Two types of curing methods are used in glulam production, a cold cure method and radio frequency curing. Radio frequency curing requires electricity to generate heat, while cold curing requires only ambient temperatures. The manufacturing process can be divided into four major parts: 1. drying and grading lumber, 2. end jointing the lumber into longer laminations, 3. face bonding the laminations, and 4. finishing and fabrication.

Lumber grading

To minimize dimensional changes, the lumber must be kiln-dried to a maximum moisture content of 16 percent[3] at the lumber facility as re-drying does not occur at SE glulam facilities. Two types of lumber grading systems used in glulam manufacturing are: visual grading (L-rating), and machine grading (E-rating). The rules for L-grading are based entirely upon apparent visual characteristics. E-rated lumber is graded by a combination of lumber stiffness and visual characteristics (AITC 1983; WWPA 1994).

End jointing

To manufacture glulam beams in lengths beyond those commonly available for lumber, the lamstock must be made longer by end jointing to the desired length. The most common end joint is a finger joint about 2.8 cm (1.1 in) long. The finger joints are machined on both ends of the lumber with special cutter heads. A structural resin generally MUF is applied and the joints in successive boards are mated. The resin is cured with the joint under end pressure and heat. Most manufacturers use a continuous radio frequency curing system for this step.

Face bonding

The laminations are planed and resin is applied with a glue extruder. Phenol-resorcinol-formaldehyde is the most commonly used resin for face bonding, but MUF resin can also be used The laminations are then assembled into the required layup and pressure is applied. Two types of curing methods are cold set or

[3] The moisture content of laminations shall not exceed 16% at the time of gluing, except when it is known that the equilibrium moisture content of the laminated timber in use will be 16% or more, the moisture content of the laminations at the time of gluing shall not exceed 20% (AITC 1983).

cold cure (that uses only pressure and ambient heat for curing) and radio frequency curing which uses pressure and heat at 200+°F.

Finishing and Fabrication

After pressing and curing beams are removed from the presses and the wide faces are planed to remove adhesive that has squeezed out during pressing. The remaining two faces of the member may be lightly planed or sanded. For premium and architectural classifications, knots and planer skips are covered up. Depending upon use, final cuts are made, holes are drilled, connectors are added, and a finish may be applied. Each beam is individually wrapped for protection before shipping. Final product density, excluding resin was 560 kg/m^3. The single unit process inputs and outputs collected from surveys are listed in table 8.

Table 8 Unit Process Inputs/Outputs for Glued-Laminated Timbers Production (1 m^3), SE.

Products	**Value**	**Unit/m^3**	**Allocation (%)**
Glue-laminated timber	1	m^3	82.43
Co-products (sawdust, shavings, trimmings)	118.69	kg	17.58
Materials/fuels	**Value**	**Unit/m^3**	
Electricity, at Grid	98.88	kWh	
Natural gas	26.39	m^3	
Diesel	0.66	L	
LPG	0.41	L	
Gasoline	0.39	L	
Transport	296.89	tkm	
Melamine urea formaldehyde resin	0.77	kg	
Phenol Resorcinol Formaldehyde resin	7.96	kg	
Sawn Lumber, rough, kiln dried	567.18	kg	
Sawn Lumber, rough, green	102.03	kg	
Wrapping material – Packaging	2.05	kg	
Strap Protectors – Packaging	2.23	kg	
Strapping – Packaging	0.38	kg	
Spacers – Packaging	na		
Emissions to air	**Value**	**Unit/m^3**	
Particulates, unspecified	0.8970	kg	
VOC, volatile organic compounds	0.8297	kg	
Emission, unspecified	0.4197	kg	

3.3.2.8 Packaging

Materials used for packaging glulam for shipping are shown in Table 9. Packing materials for represent 0.83 percent (4.66 kg/m^3) of the cumulative mass of the model flow. The strap protectors, wrapping material, and strapping represent 48, 44, and 8 percent of the packaging by mass.

Table 9 Materials used in packaging and shipping per m^3, SE Glulam

Material	Value	Unit
Wrapping Material – HDPE and LDPE laminated paper	2.05	kg
Metal Strapping	0.38	kg
Cardboard strap protectors	2.23	kg
Wooden spacers	-	kg

4 Cut-off rules

According to the PCR, if the mass of a flow is less 1% of the cumulative mass of the model flow it may be excluded, provided its environmental relevance is minor. With the exception of packaging, raw materials used in small quantities that comprise less than 1% of the product mass were not included in the LCI.

5 Data quality requirements

Manufacturing plants provided data in terms of glulam and co-product production, raw materials, electricity and fuel use, and emissions. Total annual production from glulam production from the SE region was 327,872 m^3 (139 million board feet nominal) [4] which represents 39 percent of the total US production (APA 2001). The glulam producers surveyed represent 43 percent of the region's production. Total annual production from producers surveyed was 141,528 m^3 (60 million board feet, nominal). An external critical review of the survey procedures, data, analysis, and report was done for compliance with CORRIM and ISO 14040 standards (Werner, 2004).

6 Life cycle inventory analysis

6.1 Data collection

Primary data for the LCI was collected through surveys in accordance with CORRIM and ISO 14040 protocols. Primary data was collected through a survey of glulam manufacturers in the SE region. To conduct the survey, glulam plants in Alabama, Arkansas, Florida, Georgia, Louisiana, Mississippi, and Texas were preliminarily screened and identified based on their production capability and representativeness of the industry. Three plants agreed to participate in the survey.

6.2 Calculation rules

Fuel consumption was calculated per seedling and then multiplied by the number of planted seedlings per unit area specified for each of the three management scenarios to determine fuel consumption rates per unit area. Total fuel consumption per unit area was divided by the final harvested volume per unit area to establish the contribution of fuel consumption for site preparation, seedlings, and planting per unit of harvested volume.

To determine the environmental burdens of equipment used for forest extraction part of the forest management life cycle stage (Figure 2) the applicable fuel and oil consumption rates were developed for each equipment component within the harvesting system (Table 2). These data were derived from existing

[4] Nominal size-The size designation for most lumber. In lumber, the nominal size usually is greater than the actual dimension; a kiln dried 2x4 (nominal) is surfaced to 1-1/2 x 3-1/2 inches (actual).

studies for the types of harvesting equipment used in the region and included both published information and personal interviews with timber harvesting contractors (Biltonen 2002; Keegan et al. 1995; Kellogg and Bettinger. 1995; Kellogg et al. 1996; Lawson 2002; Reynolds 2002). Production and consumption factors of the harvesting system were calculated by adding the emissions for each piece of equipment used per m^3 of production.

The weight of the input wood (lumber) was determined by converting board feet[5] (nominal) to cubic feet (actual). An actual to nominal ratio was calculated based on average percentages of each size beam produced. All data from the survey was weight averaged based on a particular mill's production in comparison to the total survey production for the year. This approach resulted in a plywood production complex that represents a composite of the mills surveyed, but may not represent any mill in particular. Missing data is defined as data not reported in surveys by the glulam facilities. Missing data were carefully noted so they were not averaged as zeros. When data was missing for a variable, the weighted average for that variable reflected those facilities reporting the data in the surveys. The USLCI database was used to assess off-site impacts associated with the materials and energy used. SimaPro, version 7+ (Pré Consultants 2012) was used as the accounting program to track all of the materials, and their allocation among products and co-products.

6.3 Allocation rules

All allocation was based on the mass of the products and co-products.

6.4 LCI Results

Life cycle inventory results for glulam are presented by two life stages, 1) forestry operations, 2) glulam production (Tables 10- 13). The majority of the raw material energy consumption occurs during manufacturing with only a small portion arising from forestry operations. Embedded in wood production is the lumber production process for producing green or dry, rough lamstock and the production of MUF and PRF resins. All primary transportation steps are assigned to the wood production phase. Glulam production (wrapped up) encompasses lamstock and resin production. Raw material energy requirements are presented in Table 10 for 1 m^3 of glulam. Air emissions are reported in Table 11, water emissions are reported in Table 12 and solid waste emissions are reported in Table 13.

Table 10 Raw material energy consumption per 1 m^3 Glue-Laminated Timbers, SE.

Fuel	Total	Forestry Operations	Glulam Production
	kg/m^3		
Coal, in ground	41.8317	0.2081	41.6236
Gas, natural, in ground	28.3590	0.7540	27.6050
Oil, crude, in ground	19.2296	3.1363	16.0933
Uranium oxide, in ore	0.0012	0.0000	0.0011
Wood waste	105.3458	0.0000	105.3458

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

Table 11 Air emissions released per 1 m^3 of Glue-Laminated Timbers, SE.

Air Emission[1/]	Total	Forestry Operations	Glulam Production
	kg/m^3		
Carbon dioxide, fossil	199.0000	10.3000	188.0000
Carbon dioxide, biogenic	185.0000	0.0089	185.0000
Particulates, unspecified	1.3600	0.0013	1.3600
Sulfur dioxide	1.2900	0.0237	1.2700
VOC, volatile organic compounds	1.1900	0.0054	1.1900
Nitrogen oxides	1.0100	0.1850	0.8270
Carbon monoxide	0.5710	0.0000	0.5710
Methane	0.5500	0.0214	0.5280
Carbon dioxide	0.5300	0.4590	0.0711
Carbon monoxide, fossil	0.4920	0.0923	0.4000
Particulates, > 2.5 um, and < 10um	0.4910	0.0000	0.4850
Particulates, < 2.5 um	0.4030	0.0000	0.4030
Emission, unspecified	0.3510	0.0000	0.3510
Sulfur oxides	0.0950	0.0103	0.0848
Methane, fossil	0.0932	0.0022	0.0910
NMVOC, non-methane volatile organic compounds, unspecified origin	0.0489	0.0062	0.0427
Metals, unspecified	0.0402	0.0000	0.0402
Hydrogen chloride	0.0387	0.0001	0.0385
Isoprene	0.0166	0.0002	0.0163
Dinitrogen monoxide	0.0115	0.0027	0.0088
Benzene	0.0095	0.0001	0.0095
BTEX (Benzene, Toluene, Ethylbenzene, and Xylene), unspecified ratio	0.0093	0.0000	0.0091
Chlorine	0.0090	0.0000	0.0090
Cumene	0.0053	0.0000	0.0053
Formaldehyde	0.0044	0.0001	0.0044
Particulates, > 10 um	0.0040	0.0000	0.0040
TOC, Total Organic Carbon	0.0038	0.0000	0.0038
Acrolein	0.0038	0.0000	0.0038
Ammonia	0.0033	0.0004	0.0028
Sulfate	0.0028	0.0000	0.0028
Hydrogen fluoride	0.0026	0.0000	0.0026
Propene	0.0023	0.0001	0.0021
Hydrogen	0.0019	0.0000	0.0019
Radionuclides (Including Radon)	0.0016	0.0000	0.0016
Manganese	0.0015	0.0000	0.0015
Hydrocarbons, aliphatic, alkanes, unspecified	0.0012	0.0000	0.0012
Sulfur trioxide	0.0011	0.0000	0.0011
Acetaldehyde	0.0010	0.0000	0.0009
Acetic acid	0.0009	0.0000	0.0009
Aldehydes, unspecified	0.0007	0.0001	0.0006
Methanol	0.0007	0.0000	0.0007
Toluene	0.0006	0.0000	0.0006
Monoethanolamine	0.0006	0.0000	0.0006

Air Emission[1/]	Total	Forestry Operations	Glulam Production
	kg/m³		
Carbon dioxide, land transformation	0.0005	0.0000	0.0005
Chloroform	0.0005	0.0000	0.0005
Hydrocarbons, unspecified	0.0003	0.0000	0.0003
Ethane	0.0003	0.0000	0.0003
Methane, dichloro-, HCC-30	0.0003	0.0000	0.0003
Water	0.0003	0.0000	0.0003
Aluminium	0.0003	0.0000	0.0003
Methane, biogenic	0.0003	0.0000	0.0003
Phenol	0.0003	0.0000	0.0003
Butene	0.0003	0.0000	0.0003
Isocyanic acid	0.0002	0.0000	0.0002
Magnesium	0.0002	0.0000	0.0002
Ethene	0.0002	0.0000	0.0002
Organic substances, unspecified	0.0002	0.0000	0.0002
Nitrobenzene	0.0002	0.0000	0.0002
Propane	0.0002	0.0000	0.0002
Chloroacetic acid	0.0001	0.0000	0.0001
Pentane	0.0001	0.0000	0.0001
Ethanol	0.0001	0.0000	0.0001
Nitrogen, total	0.0001	1.0000	0.0000
Butane	0.0001	2.0000	0.0001

1/ Due to the extensive list of air emissions, totals smaller than 10^{-4} are not shown.

Waterborne emissions are all off-site (Table 12). Most wood processing facilities operate with this restriction. The water sprayed on logs for lumber production is collected and recycled or soaks into the ground. Water used at the boiler and kilns is evaporated.

Table 12 Emissions to water released per 1 m³ of Glue-Laminated Timbers, SE.

Water emission[1/]	Total	Forestry Operations	Glulam Production
	kg/m³		
Solved solids	8.1500	0.6490	7.5100
Chloride	7.8800	0.5260	7.3600
Sodium, ion	2.6400	0.1480	2.4900
Calcium, ion	0.6980	0.0468	0.6510
Sulfate	0.4850	0.0012	0.4840
Suspended solids, unspecified	0.2800	0.0329	0.2470
COD, Chemical Oxygen Demand	0.2130	0.0049	0.2080
BOD5, Biological Oxygen Demand	0.1930	0.0026	0.1900
Magnesium	0.1580	0.0092	0.1490
Lithium, ion	0.1290	0.0037	0.1250
Barium	0.1110	0.0147	0.0968
Bromide	0.1040	0.0031	0.1010
Silicon	0.0800	0.0000	0.0800

Water emission[1/]	Total	Forestry Operations	Glulam Production
	kg/m³		
TOC, Total Organic Carbon	0.0422	0.0000	0.0422
DOC, Dissolved Organic Carbon	0.0420	0.0000	0.0420
Potassium, ion	0.0346	0.0000	0.0346
Carbonate	0.0310	0.0000	0.0310
Iodide	0.0255	0.0000	0.0255
Phosphate	0.0234	0.0099	0.0135
Iron	0.0194	0.0022	0.0172
Fluoride	0.0179	0.0132	0.0048
Nitrate	0.0174	0.0000	0.0174
Benzene	0.0159	0.0000	0.0159
Ammonium, ion	0.0150	0.0000	0.0150
Oils, unspecified	0.0127	0.0003	0.0123
Cumene	0.0126	0.0000	0.0126
Iron, ion	0.0124	0.0000	0.0124
Chloroacetic acid	0.0116	0.0000	0.0116
Strontium	0.0114	0.0000	0.0106
Aluminium	0.0112	0.0000	0.0112
Formate	0.0096	0.0000	0.0096
Solids, inorganic	0.0079	0.0000	0.0079
Benzene, chloro-	0.0063	0.0000	0.0063
Propene	0.0054	0.0000	0.0054
Aluminum	0.0054	0.0000	0.0043
Acetic acid	0.0049	0.0000	0.0049
Ethanol	0.0041	0.0000	0.0041
Manganese	0.0040	0.0000	0.0039
Ammonia	0.0027	0.0003	0.0025
Chlorate	0.0027	0.0000	0.0027
Borate	0.0026	0.0000	0.0026
Formaldehyde	0.0025	0.0000	0.0025
Sulfur	0.0019	0.0000	0.0018
Suspended solids, inorganic	0.0014	0.0000	0.0014
Acetaldehyde	0.0013	0.0000	0.0013
Sulfide	0.0012	0.0000	0.0012
Phenol	0.0012	0.0000	0.0012
Boron	0.0010	0.0000	0.0009
Nitrobenzene	0.0008	0.0000	0.0008
Toluene	0.0007	0.0000	0.0007
Zinc, ion	0.0007	0.0000	0.0007
Methanol	0.0006	0.0000	0.0006
Dimethylamine	0.0006	0.0000	0.0006
Chloramine	0.0004	0.0000	0.0004
Benzene, 1,2-dichloro-	0.0004	0.0000	0.0004
Barite	0.0004	0.0000	0.0004
Phosphorus	0.0004	0.0000	0.0004
Silver	0.0004	0.0000	0.0004

Water emission[1/]	Total	Forestry Operations	Glulam Production
	kg/m^3		
Nickel, ion	0.0004	0.0000	0.0004
Bromate	0.0004	0.0000	0.0004
Titanium, ion	0.0003	0.0000	0.0003
Nitrogen, total	0.0003	0.0000	0.0003
Aniline	8.1500	0.6490	7.5100
Cyanide	7.8800	0.5260	7.3600
Ethane, 1,2-dichloro-	2.6400	0.1480	2.4900
Propionic acid	0.6980	0.0468	0.6510
Zinc	0.4850	0.0012	0.4840
Ethylene oxide	0.2800	0.0329	0.2470
Carboxylic acids, unspecified	0.2130	0.0049	0.2080
Benzoic acid	0.1930	0.0026	0.1900
2-Propanol	0.1580	0.0092	0.1490
Detergent, oil	0.1290	0.0037	0.1250
Copper, ion	0.1110	0.0147	0.0968
Xylene	0.1040	0.0031	0.1010
Chromium	0.0800	0.0000	0.0800
Toluene, 2-chloro-	0.0422	0.0000	0.0422
Nitrogen	0.0420	0.0000	0.0420
Lead	0.0346	0.0000	0.0346
Diethylamine	0.0310	0.0000	0.0310
Butene	0.0255	0.0000	0.0255
Ethylamine	0.0234	0.0099	0.0135
Cobalt	0.0194	0.0022	0.0172

1/ Due to the extensive list of air emissions, totals smaller than 10^{-4} are not shown.

Solid emissions include waste generated from all chemical, fuel, resin, and wood production facilities (Table 13). Glulam manufactures reported solid waste collected in pollution abatement devices. Of the total solid waste generated, 24 percent originated on-site from glulam production. The solid waste generated represented less than 7 percent by mass of glulam timbers.

Table 13 Waste to treatment per 1 m^3 of Glue-Laminated Timber, SE

Waste to treatment	Total	Forestry Operations	Glulam Production
	kg/m^3		
Solid waste	37.36	0.19	37.18

7 Life cycle impact assessment

The life cycle impact assessment (LCIA) phase establishes links between the life cycle inventory results and potential environmental impacts. The LCIA calculates impact indicators, such as global warming potential and smog. These impact indicators provide general, but quantifiable, indications of potential environmental impacts. The target impact indicator, the impact category, and means of characterizing the impacts are summarized in Table 14. Environmental impacts are determined using the TRACI method (Bare et al. 2011). These five impact categories are reported consistent with the requirement of the wood products PCR (PCR 2011).

Table 14 Selected impact indicators, characterization models, and impact categories

Impact Indicator	Characterization Model	Impact Category
Greenhouse gas (GHG) emissions	Calculate total emissions in the reference unit of CO_2 equivalents for CO_2, methane, and nitrous oxide.	Global warming
Releases to air decreasing or thinning of ozone layer	Calculate the total ozone forming chemicals in the stratosphere including CFC's HCFC's, chlorine, and bromine. Ozone depletion values are measured in the reference units of CFC equivalents.	Ozone depletion
Releases to air potentially resulting in acid rain (acidification)	Calculate total hydrogen ion (H+) equivalent for released sulfur oxides, nitrogen oxides, hydrochloric acid, and ammonia. Acidification value of H^+ mole-eq. is used as a reference unit.	Acidification
Releases to air potentially resulting in smog	Calculate total substances that can be photo-chemically oxidized. Smog forming potential of O_3 is used as a reference unit.	Photochemical smog
Releases to air potentially resulting in eutrophication of water bodies	Calculate total substances that contain available nitrogen or phosphorus. Eutrophication potential of N-eq. is used as a reference unit.	Eutrophication

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 that no single indicator is given more or less value than any of the others. Additionally, each impact indicator value is stated in units that are not comparable to others. For the same reasons, indicators should not be combined or added. Table 15 provides the environmental impact by category for softwood plywood produced in the SE region. It addition, energy and material resource consumption values and the waste generated are also provided.

Table 15 provides the environmental impact by category for one cubic meter of glulam produced in the SE region. In addition, energy and material resource consumption values and the waste generated are also provided. Environmental performance results for global warming potential (GWP), acidification, eutrophication, ozone depletion and smog, energy consumption from non-renewables, renewables, wind, hydro, solar, and nuclear fuels, renewable and nonrenewable resources, and solid waste are shown in Table 15. For GWP, 94 percent of the CO_2 equivalent emissions come from producing glulam, with remainder assigned to forestry operations. . Values in Table 15 are the cumulative impact of all upstream processes required for glulam production including those from forestry, lamstock, resin, and packaging production and transportation energy required to move these materials to the glulam facility.   For example, differences between Glulam Production data in table 8 with results in table 15 are a result of the resources and fuels used in the upstream processes, i.e. fresh water use.

Table 15 Environmental performance of 1 m^3 Glue-Laminated Timbers, SE.

Impact category	Unit	Total	Forestry Operations	Glulam Production
Global warming potential (GWP)	kg CO_2 equiv	218.67	12.19	206.48
Acidification Potential	H+ moles equiv	113.36	9.18	104.19
Eutrophication Potential	kg N equiv	0.1420	0.0324	0.1096
Ozone depletion Potential	kg CFC-11 equiv	0.0000	0.0000	0.0000
Smog Potential	kg O3 equiv	29.90	4.61	25.29
Total Primary Energy Consumption	**Unit**	**Total**	**Forestry Operations**	**Glulam Production**
Non-renewable fossil	MJ	3,514.76	189.18	3,325.58
Non-renewable nuclear	MJ	438.70	1.81	436.89
Renewable (solar, wind, hydroelectric, and geothermal)	MJ	17.16	0.20	16.96
Renewable, biomass	MJ	2,213.25	0.00	2,213.25
Material resources consumption (Non-fuel resources)	**Unit**	**Total**	**Forestry Operations**	**Glulam Production**
Non-renewable materials	kg	4.89	0.00	4.86
Renewable materials	kg	587.80	0.00	587.80
Fresh water	L	1,092.44	0.05	1,092.40
Waste generated	**Unit**	**Total**	**Forestry Operations**	**Glulam Production**
Solid waste	kg	37.36	0.19	37.18

8 Treatment of biogenic carbon

Treatment of biogenic carbon is consistent with the Intergovernmental Panel for Climate Change (IPCC 2006) inventory reporting framework in that there is no assumption that biomass combustion is carbon neutral, but that net carbon emissions from biomass combustion are accounted for under the Land-Use Change and Forestry (LUCF) Sector and are therefore ignored in energy emissions reporting for the product LCA to prevent double counting. Standards such as ASTM D7612, which are used in North America to define legal, responsible and/or certified sources of wood materials, are in place to provide assurances regarding forest regeneration and sustainable harvest rates that serve as proxies to ensure stable carbon balances in the forest sector. They are outside the accounting framework for this LCA.

This approach to the treatment of biogenic carbon was taken for the Norwegian Solid Wood Product PCR (Aasestad 2008), and the North American PCR has adopted an identical approach to ensure comparability and consistency. The North American PCR approach is followed here for GWP reporting therefore the default TRACI impact assessment method was used. This default method does not count the CO_2 emissions released during the combustion of woody biomass during production. Other emissions associated from wood combustion, e.g., methane or nitrogen oxides, do contribute to and are included in the GWP impact category. For a complete list of emissions factors for the GWP method used, see Bare et al. (2011). Using this method, 219 kg CO_2e were released in the production of 1 m^3 of glulam (including lamstock and resin production). That same 1 m^3 of glulam stores 1,010 kg CO_2e (Table 16).

Table 16 Carbon balance per 1 m^3 softwood Glue-Laminated Timbers, SE

	kg CO_2 equivalent
released forestry operations	12.19
released manufacturing	206.48
CO_2 eq. stored in product	1,009.91

9 Conclusions

The cradle to gate LCA for glued-laminated timbers includes the LCI of forest resources that relies on secondary and tertiary data and the LCI of manufacturing of glue-laminated timbers that relies on primary survey data and secondary data on process inputs such as natural gas, diesel, and electricity. The survey results were representative of glue-laminated timbers in the SE region. Glulam production reported in surveys were representative of the production processes and volumes of timbers consistent with trade association production data.

To produce one cubic meter of finished product glulam in the SE, it took 693 kg of roundwood. The roundwood produced 560 kg of lamstock for the production of 551 kg (1 m^3 w/o resin) of glulam and 99 kg of coproduct (sawdust, trimming, shavings). No self-generated fuel was used in the glulam manufacturing process. Self-generated fuel was used in the production of the lamstock material and is reported in the SE lumber manufacturing report.

Emissions from the forest resources LCI and LCIA are small relative to manufacturing emissions. The glulam manufacturing process has some onsite emissions from end jointing and face bonding of the laminations with the resins. The production of lumber for glulam and the manufacturing of resins consumed a greater amount of energy during processing over glulam production and consequently consumed the highest level of energy.

The majority of the energy consumption comes from non-renewable fossil fuel for both forestry operations and wood production representing 99 and 55 percent, respectively. The wood production process (lumber, glulam and resins production included) uses 37 percent renewable biomass fuels.

The TRACI impact method does not count the contribution of wood-derived CO_2 emissions from burning wood fuel in the boiler towards the global warming impact estimate. This is consistent with the current US EPA ruling on wood emissions from stationary sources which considers the CO_2 taken up by the forest ecosystem when the tree grew as balancing any CO_2 emissions when it is burned. Under the TRACI method, combustion of fossil fuels generates CO_2 and other air emissions that contribute to the global warming impact. Using the TRACI method 207 kg CO_2e were released in the production of 1 m^3 of glulam. That same 1 m^3 of glulam stores 1,010 kg CO_2e.

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