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

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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 Pacific Northwest (PNW) region. The PNW regional data is a representative cross-section of forest growth and manufacturing processes in western Washington and Oregon. This document updates the current glulam LCI from a gate to gate to a cradle to gate LCI Updates include the addition of PNW forestry operations, boiler, resin, and electrical grid data that have been developed since the original mill surveys were conducted in the 1999 and 2000 time period. 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 report 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 PNW 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 PNW region. Lumber production was obtained from Milota et al. (2005) and Puettmann et al. (2012) reports. The logs for lumber production are obtained from the forest resource base located in western Washington and Oregon as representative of the 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).

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.

Their uses are 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. Over one-half (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 remaining glulam goes to 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 and can be made of various species in the PNW region with Douglas-fir (*Pseudotsuga menziesii,* (Franco) Mirb.) dominating, but western larch (*Larix occidentalis,* Nutt.) and Alaskan yellow cedar (*Chamaecyparis nootkatensis,* (D. Don) Spach) are also used.

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 PNW are shown in Table 1.

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

Lamstock sizes for glulam (actual)				Percent
Width	**Depth**	**Width**	**Depth**	
mm		**inch**		
44.45	95.25	1.75	3.75	25
44.45	149.35	1.75	5.88	55
44.45	196.85	1.75	7.75	15
44.45	247.65	1.75	9.75	5

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 Pacific Northwest and ends with glulam timbers (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 with the transportation of logs, and plywood 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.

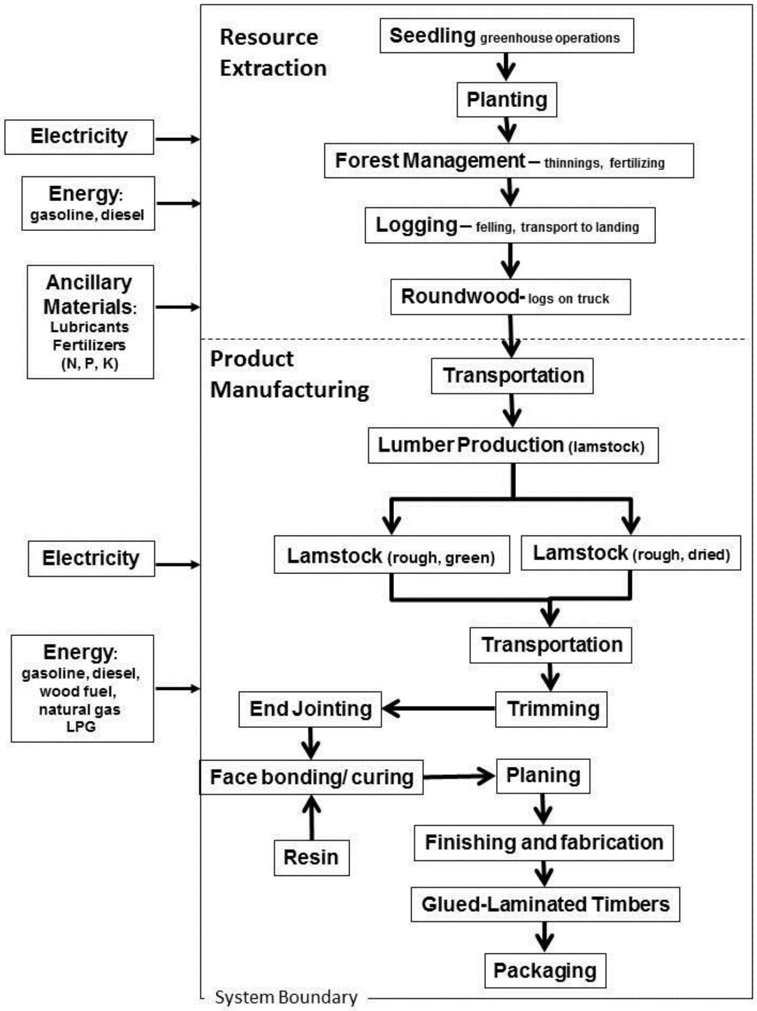

Figure 2 Cradle to gate life cycle stages for Glue-Laminated Timbers, PNW.

3.3 Description of data/Process Description

3.3.1 Forestry Operations

Forestry operations include growing seedlings, planting, thinning, fertilization (where applicable) and final harvest. The specific processes involved are reforestation: which includes seedling production, site preparation, planting, pre-commercial thinning, 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 thinning, and harvest operations. The primary output product for this analysis is a log destined for the lumber mill or plywood mill. The co-product, non-merchantable slash, is generally left at a landing. Slash disposal was not modeled as it was assumed to decay in-situ.

Logs used in the production of softwood plywood in the PNW 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. Only 12% of stands in the PNW have fertilizer applications, while 58% have thinning operations.

In the PNW most harvested volume comes from forest operations on private lands where investment in timber is the precursor to harvest. For all non-federal land managers in the region, reforestation is a statutory requirement as harvests are administered under state forest practices acts. Harvested lands are reforested for the next crop cycle with the sequence of treatments from planting to harvest averaging 45 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 the potential productivity gains from future technologies. Outputs representing quantities of product, measures of consumed resources, and the emission factors associated with those 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 emission factors 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. Management intensities ranged from little intervention on low site productivity lands to higher management intensities involving combinations of fertilization and thinning on high productivity lands. Associated with each combination of management intensity and site productivity is an estimated yield of biomass based on forest growth and yield generated using the Forest Vegetation Simulator (FVS) growth and yield model (Wykoff 1986). FVS is developed from empirical data on forest growth and provides a reasonable estimate of standing and harvested biomass along with other stand attributes through time from seedling establishment to final harvest of the forest stand at rotation age.

Inputs to the forest resources system include site preparation activities required to prepare a site for planting, seedlings, electrical energy required to operate forest nursery pumps and to keep seedlings cool for planting, the human effort required to hand plant seedlings, fertilizer used during seedling production and stand growth, and the fuel and lubricants needed to power and maintain the harvesting system(s) equipment. 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 assumed to decay in-situ.

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 PNW were developed from personal communication with forest nursery managers (Wenny 2003) and published documentation of greenhouse operations for containerized seedlings (Schlosser et al. 2003). All seedlings in the PNW were planted by hand. The only energy factors associated with planting were related to travel to and from the planting site.

Stand treatment operations were based on growth and yield modeling and management scenarios developed at the University of Washington (Lippke and Comnick 2002). Fertilization also occurred once seedlings were planted in the forest for the subset of hectares that were in higher management intensities. Fertilization was done in years 20, 30, and 40 on acres in the high-intensity management class and the environmental burdens associated with these efforts are included as part of the reforestation process. 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	12	12	12	12
Seedlings, at greenhouse	p[1]	988	1,482	1,482	1,275
Nitrogen in fertilizer					
In Seedlings	kg	0.04	0.06	0.06	0.05
On Site	kg	-	-	396.78	47.61
Phosphorous in fertilizer		-	-	-	-
In Seedlings	kg	0.07	0.11	0.11	0.09
On Site	kg	-	-	67.25	8.07
Potassium in fertilizer		-	-	-	-
In Seedlings	kg	0.17	0.26	0.26	0.22
On Site	kg	-	-	-	-

[1] p = individual seedling

3.3.1.2 Equipment

Timber harvesting activities include five 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.

Although harvesting operations in the PNW can be found on both gentle and steep terrain, they are more likely to involve steep slope conditions that dictate the use of manual felling and cable yarding harvest systems. Variations in harvest equipment size operation (thinning versus final harvest) affect 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 (clearcut) for those management regimes that use thinning. Most final harvest operations in the PNW use clearcut harvests with retention of a minimum number of trees to meet statutory green tree retention requirements. Operations under these conditions are modeled using production rates for clearcut systems. This mix of harvest systems and the allocation of volume recovered between thinning and final harvest operations are provided in table 3.

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 Equipment allocation by treatment and management intensity

Management Intensity	Thinning	Final Harvest (usage per final volume harvested)
Low intensity site		
Chain saw	NA	100%
Cable yarder, large	NA	100%
Loader	NA	100%
Medium intensity		
Chain saw	19.6%	80.4%
Cable yard, medium	19.6%	
Cable yarder, large		80.4%
Loader	19.6%	80.4%
High intensity		
Chain saw	12.6%	87.5%
Cable yard, medium	12.6%	
Cable yarder, large		87.5%
Loader	12.6%	87.5%

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 (Table 4) based on the relative percentage of the land base they occupy. Site productivity as measured by site index, the height of dominant trees at 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 a management intensity classes. The management intensity and site productivity classes used in the Forest Service analysis were associated with, and were represented by three general management intensity combinations. Specific assumptions associated with these three scenarios are outlined in Table 4. In the PNW, 42% of the lands were classified in the lowest productivity/ management intensity class, 46% in the middle class, and 12% in the highest management intensity class. The allocation of forested area to management intensity/site productivity class produces the log volume recovered from the forest resource as shown in Table 4. Allocating per ha values from Table 2 to the total yield of 501 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 PNW.

Management intensity class prescription	Low Intensity	Medium Intensity	High Intensity	Weighted Average
	per hectare			
Rotation age (yr)	45	45	45	
Planting density (trees per hectare)	988	1,482	1,482	1,275

Fertilization	None	None	Years 20, 30, 40	
Pre-commercial thinning	None	Year 15	Year 15	
Final thinned density (Trees per hectare)	0	*740*	*680*	
Commercial thinning—m^3	0	81	81	47
at year		*30*	*25*	
Final harvest— m^3	433	409	701	454
at year	*45*	*45*	*45*	
Total yield/hectare— m^3	433	490	782	501
Percent sawlogs	100%	100%	100%	
Percent area in class	42%	46%	12%	

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 PNW region by major process (Table 5).

Table 5 Fuel consumption for PNW 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	0.088
Lubricants	L	0.002
Electricity	kWh	0.107
Commercial Thinning and Final Harvest		
Diesel	L	2.850
Lubricants	L	0.051
Total Forest Extraction Process		
Gasoline and Diesel	L	2.938
Lubricants	L	0.053
Electricity	kWh	0.107

3.3.2 Wood Product Manufacturing

3.3.2.1 Transportation Process

Logs are transported to lumber mills in the PNW by truck (Table 6). Lamstock (lumber) are 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 beam is strapped and wrapped before shipping. All flow analyses of wood process were determined on an oven-dry weight specific gravity[1] of 0.47.

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

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

Material delivered to mill	Delivery Distance	
Material	**kilometers**	**miles**
Logs to Lumber/Lamstock Production	113	70
Lamstock, green	52	32
Lamstock, dry	139	86
Resin (PRF and MUF)	70	43
Steel strapping - Packaging	811	504
Wrapping material - Packaging	172	107

3.3.2.2 Energy use and generation

A small amount of purchased wood fuel was used in a boiler for heat input for drying green lamstock in a kiln and for process heating for glulam production in the PNW. Most of the wood fuel used to make glulam was consumed during lamstock production (Milota et al. 2005) (Table 7). The production of lamstock used in glulam production contributed 77 percent to the total wood fuel consumption. The remainder 23 percent is picked up at the glulam facility for redrying lumber or drying green lumber as well as facility heating which is required for proper curing of adhesives and for keeping the lamstock at the required moisture content.

Table 7 Boiler inputs for drying lumber per 1 m^3 Glue-laminated Timbers, PNW.

Fuel	Unit	Value (Unit/m^3)	HHV (MJ/kg)	MJ/m^3 of product	Percent Contribution (%)
Wood fuel - Glulam	kg	23	20.9	481.16	23
Wood fuel – Lamstock Production	kg	79.03	20.9	1,651.10	77
TOTAL		**102.03**		**2,132.26**	

The USLCI database was used for boiler processes inputting wood fuel (NREL 2012) (Table 8). These boiler processes are based on the US Environmental Protection Agency (EPA) AP-42, Compilation of Air Pollutant Emission Factors (EPA 1998, 2006, 2010). The AP-42 emission factors assume no emission controls and therefore likely over-estimates the impact factors for wood emissions.

Table 8 Wood Boiler Process for Glulam production.

Product	Value	Unit/m3
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
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 PNW 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) either green or 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 60percent non-volatile solids content. PRF resins differ somewhat from the other resins in that

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

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, 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 for curing MUF resins. The surveys indicated both radio frequency (81%) and cold cure (19%) processes were used in PNW 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 12% 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 drying and grading

To minimize dimensional changes, the lumber must be kiln-dried to a maximum moisture content of 16 percent[3]. Lumber used may be purchased green and dried. Lumber (lamstock) with a moisture content greater than the threshold are removed from the process and re-dried. Re-drying is accomplished through either air or kiln drying. 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).

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[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).

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, such as 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 lamstock are planed and resin is applied with a glue extruder. Phenol-resorcinol-formaldehyde is the most common 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 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 484 kg/m^3. The single unit process inputs and outputs collected from surveys are listed in table 9.

Table 9 Unit Process Inputs/Outputs for Glued-Laminated Timbers Production (1 m^3), PNW.

Products	Value	Unit/m^3	Allocation (%)
Glue-laminated timber	1	m^3	81.67
Co-products (sawdust, shavings, trimmings)	108.30	kg	18.33
Materials/fuels	**Value**	**Unit/m^3**	
Electricity, at Grid	84.44	kWh	
Natural gas	3.98	m^3	
Diesel	0.36	L	
LPG	1.62	L	
Gasoline	17.46	L	
Wood waste combusted in industrial boiler	22.99	kg	
Transport	84.58	tkm	
Melamine urea formaldehyde resin	0.96	kg	
Phenol Resorcinol Formaldehyde resin	5.17	kg	
Sawn Lumber, rough, kiln dried	443.85	kg	
Sawn Lumber, rough, green	149.16	kg	
Wrapping material - Packaging	1.42	kg	
Strap Protectors - Packaging	1.54	kg	
Strapping - Packaging	0.28	kg	

Spacers - Packaging	na		
Emissions to air	**Value**	**Unit/m^3**	
Particulates, unspecified	0.6186	kg	
VOC, volatile organic compounds	0.2917	kg	
2-Propanol	0.2099	kg	
Ethanol	0.0050	kg	
Resorcinol	0.0000	kg	
Methanol	0.0104	kg	
Phenol	0.0105	kg	
Formaldehyde	0.0003	kg	

3.3.2.8 Packaging

Materials used for packaging glulam timbers for shipping are shown in Table 10. Packing materials for represent 0.66 percent (3.24 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 10 Materials used in packaging and shipping per m^3, PNW Glulam

Material	Value	Unit
Wrapping Material – HDPE and LDPE laminated paper	1.42	kg
Metal Strapping	0.28	kg
Cardboard strap protectors	1.54	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. Raw materials used in small quantities and comprise less than 1% of the product mass (excluding packaging) were not included in the LCA.

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 PNW region was 261,931m^3 (111 million board feet[4], nominal[5]) which represents 31 percent of the total US production (APA 2001). The glulam producers surveyed represent 70 percent of the region's production. Total annual production from producers surveyed was 184,060 m^3 (78 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).

[4] Board foot (BF)-The basic unit of measurement for lumber. One board foot is equal to a 1-inch board 12 inches in width and 1 foot in length

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

6 Life cycle inventory analysis

6.1 Data collection

Primary data was collected through a survey of glulam manufacturers in the PNW region. To conduct the survey, glulam plants in Oregon and Washington 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

Planting data for the PNW Forestry Operations were from personal communication with forest nursery managers (Wenny 2003) and published documentation of greenhouse operations for containerized seedlings (Schlosser et al. 2003). 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 1) 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 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; Hochrein and Kellogg 1988; Jorgenson 2002; Keegan et al. 1995; Kellogg and Bettinger. 1995; Kellogg et al. 1996; Lawson 2002; Ledoux 1984; Reynolds 2002; Stevens and Clarke 1974). 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[6] (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. 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. All conversion units for forestry and forest products were taken from *Forest Products Measurements and Conversion Factors: With Special Emphasis on the US Pacific Northwest* by Briggs (1994).

6.3 Allocation rules

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

6.4 LCI Results

Raw material energy requirements are presented in Table 11 for 1 m^3 of glulam timbers. The majority of the raw material energy consumption occurs during wood production 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. Life cycle inventory results for glulam are presented by two life stages, 1) forestry operations, 2) glulam production (Tables 11- 14).

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

Table 11 Raw material energy consumption per 1 m^3 Glue-Laminated Timbers, PNW

Fuel	TOTAL	Forestry Operations	Glulam Production
	kg/m^3		
Coal, in ground	24.0598	0.1710	23.8888
Gas, natural, in ground	29.1016	0.1538	28.9478
Oil, crude, in ground	13.2811	2.9107	10.3704
Uranium oxide, in ore	0.0005	0.0000	0.0005
Wood waste	102.0258	0.0000	102.0258

Air emission reported for forestry operations and glulam production (Table 11). Glulam production (wrapped up) encompasses lamstock and resin production.

Table 12 Air emissions released per 1 m^3 of Glue-Laminated Timbers, PNW.

Air Emission[1/]	Total	Forestry Operations	Glulam Production
	kg/m^3		
Carbon dioxide, fossil	154.0000	9.4600	144.0000
Carbon dioxide, biogenic	145.0000	0.0075	145.0000
Sulfur dioxide	1.0600	0.0062	1.0500
Nitrogen oxides	0.7460	0.1710	0.5740
Particulates, unspecified	0.5550	0.0009	0.5540
Methane	0.4830	0.0128	0.4700
Carbon monoxide	0.4530	0.0000	0.4530
Particulates, > 2.5 um, and < 10um	0.3870	0.0053	0.3810
Carbon monoxide, fossil	0.3460	0.0860	0.2600
VOC, volatile organic compounds	0.3420	0.0046	0.3380
Particulates, < 2.5 um	0.3170	0.0000	0.3170
2-Propanol	0.1740	0.0000	0.1740
Particulates, < 10 um	0.0844	0.0000	0.0844
Methane, fossil	0.0823	0.0010	0.0814
Carbon dioxide	0.0733	0.0258	0.0475
Sulfur oxides	0.0669	0.0095	0.0574
NMVOC, non-methane volatile organic compounds, unspecified origin	0.0336	0.0057	0.0279
Metals, unspecified	0.0316	0.0000	0.0316
Hydrogen chloride	0.0259	0.0001	0.0258
Isoprene	0.0200	0.0002	0.0199
BTEX (Benzene, Toluene, Ethylbenzene, and Xylene), unspecified ratio	0.0098	0.0001	0.0097
Methanol	0.0097	0.0000	0.0097
Phenol	0.0089	0.0000	0.0089
Particulates, SPM	0.0082	0.0000	0.0082

Air Emission[1/]	Total	Forestry Operations	Glulam Production
	kg/m^3		
Benzene	0.0067	0.0000	0.0067
Dinitrogen monoxide	0.0067	0.0002	0.0065
Chlorine	0.0059	0.0000	0.0059
Ethanol	0.0042	0.0000	0.0042
Formaldehyde	0.0038	0.0001	0.0037
Cumene	0.0034	0.0000	0.0034
TOC, Total Organic Carbon	0.0030	0.0000	0.0030
Acrolein	0.0030	0.0000	0.0030
Particulates, > 10 um	0.0028	0.0000	0.0028
Ammonia	0.0027	0.0001	0.0026
Sulfate	0.0018	0.0000	0.0018
Propene	0.0015	0.0001	0.0014
Hydrogen fluoride	0.0015	0.0000	0.0015
Hydrogen	0.0013	0.0000	0.0013
Manganese	0.0012	0.0000	0.0012
Acetaldehyde	0.0011	0.0000	0.0011
Hydrocarbons, aliphatic, alkanes, unspecified	0.0008	0.0000	0.0008
Sulfur trioxide	0.0007	0.0000	0.0007
Radionuclides (Including Radon)	0.0006	0.0000	0.0006
Acetic acid	0.0006	0.0000	0.0006
Aldehydes, unspecified	0.0005	0.0001	0.0004
Toluene	0.0004	0.0000	0.0004
Monoethanolamine	0.0004	0.0000	0.0004
Carbon dioxide, land transformation	0.0003	0.0000	0.0003
Chloroform	0.0003	0.0000	0.0003
Isocyanic acid	0.0003	0.0000	0.0003
Ethane	0.0003	0.0000	0.0003
Methane, dichloro-, HCC-30	0.0002	0.0000	0.0002
Water	0.0002	0.0000	0.0002
Aluminium	0.0002	0.0000	0.0002
Methane, biogenic	0.0002	0.0000	0.0002
Butene	0.0002	0.0000	0.0002
Hydrocarbons, unspecified	0.0001	0.0000	0.0001
Ethene	0.0001	0.0000	0.0001
Organic substances, unspecified	0.0001	0.0000	0.0001
Propane	0.0001	0.0000	0.0001
Magnesium	0.0001	0.0000	0.0001
Nitrobenzene	0.0001	0.0000	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 13). No mill in the survey discharged any process water. Most sawmills 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 13 Emissions to water released per 1 m^3 of Glue-Laminated Timbers, PNW.

Water emission	Total	Forestry Operations	Glulam Production
	kg/m^3		
Solved solids	7.4800	0.4920	6.9900
Chloride	6.8900	0.3990	6.4900
Sodium, ion	2.2100	0.1120	2.1000
Calcium, ion	0.6120	0.0355	0.5770
Sulfate	0.3150	0.0009	0.3140
Suspended solids, unspecified	0.2190	0.0290	0.1900
COD, Chemical Oxygen Demand	0.1540	0.0038	0.1500
Lithium, ion	0.1350	0.0008	0.1340
BOD5, Biological Oxygen Demand	0.1350	0.0020	0.1330
Magnesium	0.1340	0.0069	0.1270
Barium	0.0879	0.0129	0.0750
Bromide	0.0780	0.0024	0.0756
Silicon	0.0533	0.0000	0.0533
TOC, Total Organic Carbon	0.0275	0.0000	0.0275
DOC, Dissolved Organic Carbon	0.0274	0.0000	0.0274
Potassium, ion	0.0227	0.0000	0.0227
Carbonate	0.0200	0.0000	0.0200
Iodide	0.0164	0.0000	0.0164
Iron	0.0155	0.0019	0.0136
Nitrate	0.0112	0.0000	0.0112
Benzene	0.0103	0.0000	0.0103
Oils, unspecified	0.0102	0.0003	0.0099
Strontium	0.0101	0.0006	0.0095
Phosphate	0.0094	0.0006	0.0089
Ammonium, ion	0.0092	0.0000	0.0092
Iron, ion	0.0082	0.0000	0.0082
Cumene	0.0081	0.0000	0.0081
Chloroacetic acid	0.0074	0.0000	0.0074
Aluminium	0.0066	0.0000	0.0066
Formate	0.0062	0.0000	0.0062
Solids, inorganic	0.0052	0.0000	0.0052
Aluminum	0.0052	0.0009	0.0042

Water emission	Total	Forestry Operations	Glulam Production
	kg/m³		
Benzene, chloro-	0.0041	0.0000	0.0041
Fluoride	0.0038	0.0007	0.0031
Propene	0.0035	0.0000	0.0035
Acetic acid	0.0031	0.0000	0.0031
Ethanol	0.0026	0.0000	0.0026
Manganese	0.0026	0.0000	0.0026
Ammonia	0.0024	0.0002	0.0022
Chlorate	0.0017	0.0000	0.0017
Borate	0.0017	0.0000	0.0017
Formaldehyde	0.0016	0.0000	0.0016
Sulfur	0.0013	0.0000	0.0013
Suspended solids, inorganic	0.0010	0.0000	0.0010
Sulfide	0.0009	0.0000	0.0009
Acetaldehyde	0.0008	0.0000	0.0008
Phenol	0.0008	0.0000	0.0008
Boron	0.0008	0.0000	0.0008
Toluene	0.0005	0.0000	0.0005
Nitrobenzene	0.0005	0.0000	0.0005
Zinc, ion	0.0005	0.0000	0.0005
Methanol	0.0004	0.0000	0.0004
Dimethylamine	0.0004	0.0000	0.0004
Silver	0.0004	0.0000	0.0003
Barite	0.0003	0.0000	0.0003
Chloramine	0.0003	0.0000	0.0003
Benzene, 1,2-dichloro-	0.0003	0.0000	0.0003
Phosphorus	0.0003	0.0000	0.0003
Nickel, ion	0.0002	0.0000	0.0002
Nitrogen, total	0.0002	0.0000	0.0002
Titanium, ion	0.0002	0.0000	0.0002
Bromate	0.0002	0.0000	0.0002
Cyanide	0.0002	0.0000	0.0002
Aniline	0.0002	0.0000	0.0002
Benzoic acid	0.0002	0.0000	0.0002
Detergent, oil	0.0002	0.0000	0.0002
Zinc	0.0002	0.0000	0.0001
Ethane, 1,2-dichloro-	0.0002	0.0000	0.0002

Water emission	Total	Forestry Operations	Glulam Production
	kg/m^3		
Xylene	0.0001	0.0000	0.0001
Propionic acid	0.0001	0.0000	0.0001
Carboxylic acids, unspecified	0.0001	0.0000	0.0001
Ethylene oxide	0.0001	0.0000	0.0001
2-Propanol	0.0001	0.0000	0.0001
Nitrogen	0.0001	0.0000	0.0001
Copper, ion	0.0001	0.0000	0.0001
Lead	0.0001	0.0000	0.0001
Ammonia, as N	0.0001	0.0000	0.0001
Chromium	0.0001	0.0000	0.0001

Solid emissions include waste generated from all chemical, fuel, resin, ash from boilers, and wood production facilities (Table 14). Glulam manufactures reported solid waste collected in pollution abatement devices. Of the total solid waste generated, 4 percent originated on-site from glulam production. The total solid waste generated represented less 6 percent by mass of glulam timbers.

Table 14 Waste to treatment per 1 m^3 of glue laminated timber, PNW produced.

Waste to treatment	Total	Forestry Operations	Glulam Production
	kg/m^3		
Solid waste	31.12	0.15	30.97

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 15. 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 15 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. All are presented as equals. 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 16 provides the environmental impact by category for softwood plywood produced in the PNW region. It addition, energy and material resource consumption values and the waste generated are also provided.

Table 16 provides the environmental impact by category for one cubic meter of glulam produced in the PNW 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 16. For GWP, 94 percent of the CO_2 equivalent emissions come from producing glulam, with remainder assigned to forestry operations. Values in Table 16 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 9 with results in table 16 are a result of the resources and fuels used in the upstream processes, i.e. fresh water use.

Table 16 Environmental performance of 1 m^3 Glue-Laminated Timbers, PNW

Impact category	Unit	Total	Forestry Operations	Glulam Production
Global warming potential (GWP)	kg CO_2 equiv	169.85	9.88	159.98
Acidification Potential	H+ moles equiv	88.58	7.67	80.91
Eutrophication Potential	kg N equiv	0.0839	0.0094	0.0745
Ozone depletion Potential	kg CFC-11 equiv	0.0000	0.0000	0.0000
Smog Potential	kg O3 equiv	20.33	4.27	16.06
Total Primary Energy Consumption	**Unit**	**Total**	**Forestry Operations**	**Glulam Production**
Non-renewable fossil	MJ	2,818.46	145.29	2,673.17
Non-renewable nuclear	MJ	186.06	1.53	184.53
Renewable (solar, wind, hydroelectric, and geothermal)	MJ	124.07	0.24	126.67
Renewable, biomass	MJ	2,137.65	0.00	2,137.65
Material resources consumption (Non-fuel resources)	**Unit**	**Total**	**Forestry Operations**	**Glulam Production**
Non-renewable materials	kg	3.33	0.01	3.33
Renewable materials	kg	495.21	0.00	495.21
Fresh water	L	806.16	9.46	796.70
Waste generated	**Unit**	**Total**	**Forestry Operations**	**Glulam Production**
Solid waste	kg	29.77	0.15	29.62

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, 160 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 891 kg CO_2e (Table 17).

Table 17 Carbon balance per 1 m^3 softwood Glulam, PNW

	kg CO_2 equivalent
released forestry operations	9.88
released manufacturing	159.98
CO_2 eq. stored in product	890.75

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 softwood lumber that relies on primary survey data and secondary data. The survey results were representative of glue-laminated timbers in the PNW 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 PNW, it took 598 kg of roundwood. The roundwood produced 492 kg of lamstock for the production of 484 kg (1 m^3 w/o resin) of glulam and 90 kg of coproduct (sawdust, trimming, shavings). A small amount of purchased wood fuel, 23 kg/m^3 was used on-site by the glulam facility. 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 PNW 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 in both forestry operations and wood production representing 99 and 52 percent, respectively. The wood production process (lumber, glulam and resins production included) uses 42 percent renewable biomass fuels. The total energy consumption represented just over half the energy from non renewable fossil (54%) with the majority of the remainder consumption from renewable biomass fuels (41%).

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 160 kg CO_2e were released in the production of 1 m^3 of glulam. That same 1 m^3 of glulam stores 891 kg CO_2e.

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