Compile a Life Cycle Assessment of the OSB and Plywood Industries in the U.S.
&
Analysis of the OSB and Plywood Industries in the U.S. based on a Life Cycle Assessment

Final Research Report

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ABSTRACT

Life cycle assessment (LCA) is a methodology to compare and evaluate products or systems in a holistic manner. The methodology of an LCA includes the life cycle inventory (LCI), which lists inputs and outputs for a product within designated system boundaries. LCIs are used to develop impact assessments that calculate the effect of the product or system on the environment in categories such as global warming potential.

LCA has been applied for the comparison of wood products to non-wood alternatives. The results showed that wood processing is efficient and the environmental impacts are low compared to non-wood alternatives. These findings are beginning to be documented and promoted in standardized environmental product declarations (EPDs) that summarize the LCA and can be used for comparisons of different products. In order to produce up-to-date EPDs for the production of structural plywood and oriented strand board (OSB) in the U.S., updated LCI data are needed.

This study presents the collection and preparation of the LCI data for structural plywood and OSB produced in the U.S. The collected data are representative of the production year 2012 and will contribute to the update of the environmental product declaration (EPD) for both products.

In addition, the quality of the collected data sets will be assessed by descriptive statistical tools. The methods of the study should assist in standardizing and summarizing data sets, which are the basis for the calculation of industry-wide average values.
A comparison with previous studies and the discussions with experts from the industries revealed trends over time in the context of environmental impacts.

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CHAPTER 1 - LIFE CYCLE INVENTORY OF SOFTWOOD PLYWOOD PRODUCTION IN THE UNITED STATES

Abstract

This study presents the collection and preparation of the life cycle inventory (LCI) data for structural plywood produced in the Pacific Northwest (PNW) and Southeast (SE) regions of the U.S. Softwood plywood producers were invited to provide input and output data for the production year 2012. The collected data represent 75.18% and 33.82% of the total production output in the PNW and SE regions in the survey year, respectively.

Production-weighted average values of the collected input and output data were determined based on the functional unit of one thousand square feet (MSF) 3/8 inch basis (0.885 m^3). The collected primary data cover the environmental burdens within the gate-to-gate system boundaries. The life cycle impact assessment (LCIA) from cradle-to-gate required secondary data for the forestry operations, electricity, resin and thermal energy production from the USLCI database modeled. These data were assessed with the SimaPro 8.0 an life cycle assessment (LCA) software package by using the 'Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts' (TRACI 2.1 V1.01/US 2008) method (Bare, 2009).

The results of this study will contribute to the environmental product declaration (EPD) for softwood plywood and will assure compliance with the data quality requirements of the relevant classification standard the Product Category Rule (PCR) for North American Structural and Architectural Wood Products (FPInnovations, 2011).

Introduction

Softwood plywood is a wood-based building product that is commonly used in the U.S. for commercial and residential construction. The characteristics of plywood are based on the cross-oriented layers of sliced veneer, which are glued together (FPL, 2010).

Figure 1. Softwood plywood (Peri, 2014)

Although plywood is produced in different grades and thickness, a commonly-used unit of volume in the industry is one thousand square feet (MSF) 3/8 inch basis (0.885 cubic meters) (Briggs, 1994).

The aim of this project was to provide representative values for the inputs required for the production of softwood plywood in the Pacific Northwest (PNW) and Southeast (SE) regions in the U.S. for the production year 2012, and the associated outputs and emissions.

For the primary data collection, eighteen plywood mills in the U.S. were invited to contribute detailed production data for the assessment. The survey instrument was based on the used one in a prior study (J. B. Wilson et al., 2004), but was updated for current conditions. Of the eighteen mills contacted, seventeen provided the required input and output data for the assessment. The softwood plywood producers were clustered in the Pacific Northwest (PNW) and Southeast (SE) regions of the U.S. The PNW region is represented with mill data from Idaho, Oregon and Washington. The SE region is represented with mill data from Arkansas, Georgia, Louisiana, South Carolina, Texas and Virginia.

The survey results were separated into the two regions and production-weighted average values calculated. These values were used for a detailed analysis of the environmental impacts associated with the softwood plywood production. The results will contribute to the development of the environmental product declaration (EPD) of this wood-based building product.

The total production of softwood plywood in the PNW region was 2.789 billion square feet (MMMSF) 3/8 inch basis (2.468 million cubic meters) in 2012.

The surveyed mills located in the PNW produced 2.096 billion square feet 3/8 inch basis (1.854 million cubic meters), which represents 75% of the total production located in this region for the production year 2012. (APA, 2013a). The individual mills in the PNW region had a production output of about 46,000- 270,000 MSF 3/8 inch basis (40,710-240,000 cubic meters). The mills documented plant ages from 1950 to 1999 years. The mills employed 338 persons based on the production-weighted average.

The total production of softwood plywood in the SE region was 5.517 billion square feet (MMMSF) 3/8 inch basis (4.882 million cubic meters) in 2012.

The surveyed mills located in the SE produced 1.865 billion square feet 3/8 inch basis (1.651 million cubic meters), which represents 33% of the total production located in this region for the production year 2012. (APA, 2013a).

The individual mills in the SE region had a production output of about 100,000-520,000 MSF 3/8 inch basis (88,500-460,000 cubic meters).

The mills documented plant ages from the years 1965 to 1999 years. The mills employed 426 persons based on the production-weighted average.

Manufacturing Process of Softwood Plywood

The softwood plywood manufacturing process can be described as six main steps (Table 1).

Table 1. Description of the production flow of plywood and the associated inputs and outputs of each step

Production Process		Inputs	Outputs
1. Debarking	Bucking logs on the log yard. Debarking and cutting the logs to length. Prepare blocks for the peeling process	• Roundwood • Diesel • Electricity	• Debarked logs • Wood residues • Water emissions caused by water runoff from the log yard
2. Conditioning	Conditioning of debarked logs with hot water or steam	• Debarked logs • Thermal energy • Water	• Conditioned logs
3. Peeling and Clipping	Logs are peeled in the lathe to make veneer Veneer is clipped to size and sorted by moisture content	• Conditioned logs • Electricity	• Veneer (green) • Peeler cores • Veneer clippings and trim
4. Drying	Veneers are dried to 4-6% MC. The redrying rate for processed veneer that is not on that percentage is 2-18% accoring to the surveys	• Veneer (green) • Thermal energy • Electricity	• Veneer (dry) • Veneer downfall • Wood waste • Water vapor • Air emissions
5. Layup and Pressing	The resin is applied on the veneers and panels are composed for hot pressing	• Veneer (dry) • Resin • Thermal heat • Electricity	• Plywood • Water vapor • Air emissions
6. Trimming and Sawing	The plywood panels are sawn to appropriate dimensions	• Plywood • Electricity	• Sawn plywood • Plywood trim • Sawdust

Wood-based by-products are commonly used in the plywood industry to produce heat for the thermal energy intense processes like conditioning, drying and hot pressing (Figure 3). The boiler and the emission control processes were considered separate to the sub-units in the system boundaries. This LCI excludes the previous life stages of input materials, such as the growth and harvesting of trees, and resin production.

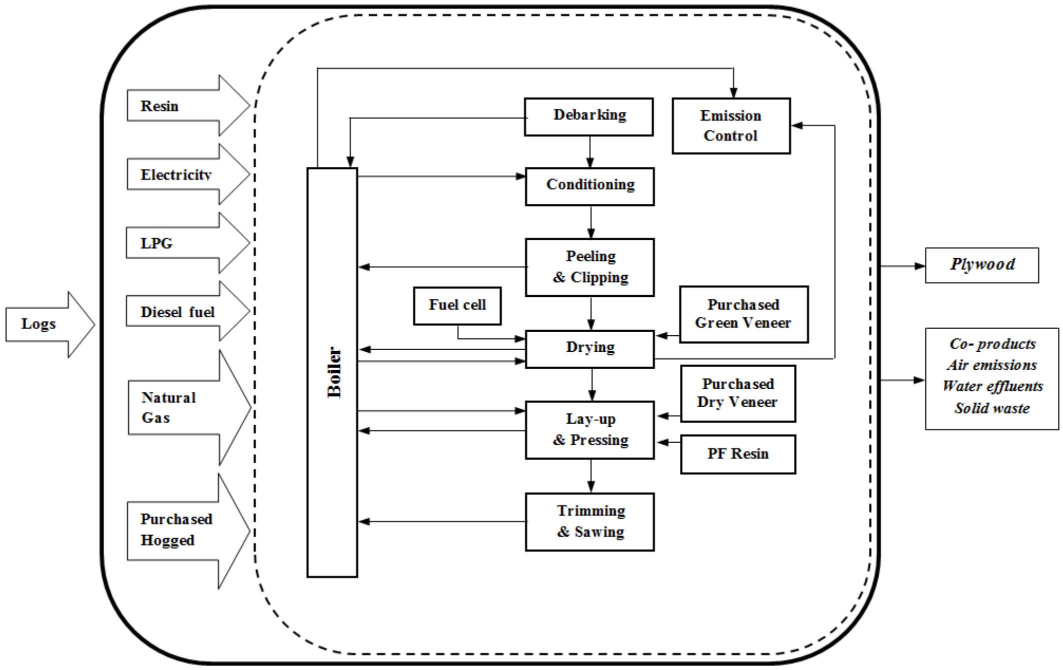

Figure 2. System boundary and sub-unit processes of softwood plywood production

Materials Flow

The materials of the LCI analysis were categorized in three main groups (Table 2).

Table 2. Input materials, co-products and products in the plywood manufacturing process

Input Materials	Co-products	Products
Logs	Bark (green)	Plywood
Veneer (green)	Chips (green)	
Veneer (dry)	Peeler cores	
Phenol formaldehyde resin	Clippings (green)	
Extender and filler	Veneer (dry)	
Catalyst	Veneer downfall (dry)	
Soda ash	Plywood trimmings (dry)	
Water	Sawdust (dry)	
Packaging Materials		

Transportation

The participating plywood mills of both regions reported transportation of their raw materials by truck and train (Tables 3, 4).

Table 3. Delivery distance of input materials for plywood production in the PNW

Material	Transportation Method	Delivery Distance (miles)[1]	Delivery Distance (km)[1]	Mills, reporting a value (n)	Weighted Coefficient of Variation (%)
Logs (roundwood)	Truck	64.42	103.67	8	44
Veneer	Truck	172.34	277.36	8	46
Veneer	Train	100.00	160.93	1	
Resin	Truck	141.13	227.12	9	75

[1]All transportation distances are weight-averaged and one way.

Table 4. Delivery distance of input materials for plywood production in the SE

Material	Transportation Method	Delivery Distance (miles)[1]	Delivery Distance (km)[1]	Mills, reporting a value (n)	Weighted Coefficient of Variation (%)
Logs (roundwood)	Truck	53.11	85.48	8	14
Logs (roundwood)	Train	62.14	100.01	1	
Veneer	Truck	143.68	231.24	4	106
Resin	Truck	105.96	170.53	8	103

[1]All transportation distances are weight-averaged and one way.

The transportation distance of hogged fuel, which is fuel for thermal energy production used for conditioning, drying and pressing was based on discussion with mill personal assumed to be within the 40 miles (64.37 km) distance in the PNW and SE regions.

Density Calculation

The wood input was provided either by volume, by cunit[1], or board feet[2] (BF) based on commonly used scaling methods such as Doyle, Scribner, or by green ton weight. The scaling method was used by twelve mills and log weight by five mills that represented 33% of the total surveyed mills' production.

As documented in the literature, the scaling methods assume the yield of sawn lumber based on the dimensions of the logs but do not accurately measure the actual wood input to the mills (Briggs, 1994). Therefore, factors for the conversion from the scaled amounts to the actual wood input were calculated based on the ratio of the wood input stated in green tons. For the Doyle scale a 2.5 conversion factor was developed; for the Scribner scale the factor was 3.2 and for cunit the value was 5.0.

To ensure consistency with the literature, the veneer recovery ratio (VRR) of the individual mills was calculated based on the actual wood input. According to the literature, the VRR has been historically between 2.5 and 3.0 SF 3/8 inch per BF (Briggs, 1994). The calculated VRR for the surveyed mill was in the range between 2.8 and 4.5. The average wood density per functional unit was calculated based on the reported wood species mix (Tables 5, 6).

[1] One cunit is 100 cubic feet (Briggs, 1994)

[2] 12 in x 12 in x 1 in (Briggs, 1994)

Table 5. Calculation of wood mass from logs for plywood production in the PNW

Wood Species	Allocation	Density[1]	Weighted Average Density		Mills, reporting a value
	(%)	(lb/ft^3)	(lb/ft^3)	(kg/m^3)	(n)
Douglas-fir	77.40	28.09	21.74	348.26	9
True fir	12.84	25.59	3.29	52.65	4
Western larch	4.19	29.96	1.26	20.12	3
Pine[2]	2.48	31.52	0.78	12.52	4
Spruce	1.64	26.22	0.43	6.91	4
Hemlock	0.82	26.22	0.22	3.46	2
Grand fir	0.62	21.85	0.13	2.16	1
Total	100.00		27.85	446.07	

[1]Density according Wood Handbook, 2010

[2]Pine species mix 50% loblolly and 50% slash assumed

Table 6. Calculation of wood mass from logs for plywood production in the SE

Wood Species	Allocation	Density[1]	Weighted Average Density		Mills, reporting a value
	(%)	(lb/ft^3)	(lb/ft^3)	(kg/m^3)	(n)
Pine[2]	95.86	31.52	30.22	483.99	8
Yellow poplar	4.14	28.72	1.19	19.05	1
Total	100.00		31.40	503.04	

[1]Density according Wood Handbook, 2010

[2]Pine species mix 50% loblolly and 50% slash assumed

Assumptions

The data collection, analysis, and assumptions followed protocols defined in the 'CORRIM Guidelines for Performing Life Cycle Inventories on Wood Products' (Puettmann et al., 2014). Additional considerations included:

- All survey data contributed by seventeen participating plywood plants were production-weighted in comparison to the total surveyed production in the PNW and SE regions for the year 2012;

- In the SE region one mill reported the usage of a small amount of poplar in the softwood plywood production. This small percentage of 4.14% (Table 6) was included into the weighted average density calculation.

- For bark, hogged fuel, wood and wood waste (green) 50% moisture content (MC) on a dry basis was assumed. For saw dust and dry wood waste, 7% MC on a dry basis was assumed;

- The stated resin components were converted to the solid content based on the percentages stated in the surveys;

- The allocation of the fossil energy sources is based on the information provided by the mills;

- 100% of diesel fuel was assigned to the debarking process to address fuel use by mobile equipment on the log yard in both regions;

- 100% of gasoline was used for mobile equipment and was assigned to the six process units in the production process in both regions;

- 88% of liquid propane gas (LPG) was used for mobile equipment in the PNW region and was assigned on the six process units. 12% were used for emission control devices for exhaust air from the drying process;

- In the SE region 83% of LPG was used for mobile equipment and was assigned to the six process units. 17% were used for emission control devices for exhaust air from the drying process;

- 45% of natural gas in the PNW region was used for emission control and 55% for the thermal energy and steam production. (Allocation based on information from two mills);

- 9% of natural gas in the SE region was used for emission control and 91% for the thermal energy and steam production. (Allocation based on information from four mills);

- In both regions resin additives such as extender and fillers, catalysts and soda ash were excluded based on the 2% rule.

- Unaccounted wood masses of 8.87 and 0.2% for the PNW and SE regions, respectively were established by the difference between reported input and output based on the weighted wood material flows (Tables 11, 12);

Data Quality Assessment and Calculation of Inventory Data

The data quality assessment included a standardized outlier detection method, the reporting of the sample size as 'Mills reporting a value (n)' and the reporting of the data variation in form of the production-weighted coefficient of variation (CV_w). These methods have now been included in the 'CORRIM Guidelines for Performing Life Cycle Inventories on Wood Products'. In general, outliers are defined as extreme observations that can have a significant impact on calculated values. In case of the collected survey data, outliers could be values that are incorrectly reported because the true value is not known or the question was misunderstood. JMP Pro 11 statistical software was used to analyze the data set. The following example (Figure 3) of the electricity inputs per one MSF 3/8 inch (0.884 cubic meter) of softwood plywood produced in the PNW and SE demonstrates the output of the software package.

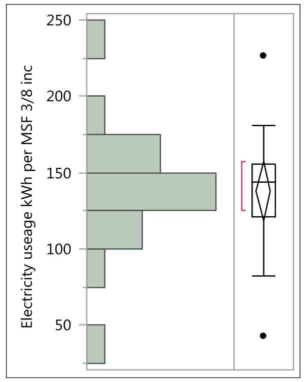

Figure 3. Distribution of reported electricity use for softwood plywood production in the PNW and SE regions combined

Outliers are shown as upper and lower dots in the box plot (Figure 3, right). In this case, two outliers were detected and discussed with the mill personal. This more in-depth analysis revealed potential biases such as a wrong electricity allocation between two on-site production lines. These two values were excluded in the calculation of the industry-average values.

The coefficient of variation (CV) describes the variability of the data series by dividing the standard deviation by the mean (Abdi, 2010). To be consistent with the documented production-weighted average values (1), the weighted standard deviation (2) was calculated. Finally, the weighted CV_w (3) was calculated and documented for the individual values (NIST, 1996) (Toshkov, 2012).

$$\bar{x}_w = \frac{\sum wx}{\sum w} \tag{1}$$

$$Sd_w = \sqrt{\sum_{i=1}^{N} w_i \, (x_i - \bar{x}_w)^2 \; x \; \frac{N'}{(N'-1)\sum_{i=1}^{N} w_i}} \tag{2}$$

$$CV_w = \frac{Sd_w}{\bar{x}_w} \tag{3}$$

The description of the data set should provide the basis for statistical analyses of future updates with the production-weighted values of 2012.

Life Cycle Inventory Results

The survey results were compiled to calculate production-weighted average values of the input (Tables 7, 8) and output (Tables 9, 10) materials associated with the production of one MSF 3/8 inch or one cubic meter of softwood plywood in the PNW and SE regions.

Table 7. Inputs gate-to-gate for softwood plywood in the PNW

Materials[1]	Unit	Quantity per MSF 3/8 inch	Unit	Quantity per m^3	Mills, reporting a value (n)	Weighted Coefficient of Variation (%)
Roundwood	ft3	5.85E+01	m3	1.87E+00		
	lb	1.63E+03	kg	8.37E+02	9	45
Bark	lb	2.19E+02	kg	1.12E+02	7	133
Phenol-formaldehyde resin	lb	2.28E+01	kg	1.17E+01	9	49
Extender and fillers[2]	lb	3.98E+00	kg	2.04E+00	9	119
Catalyst[2]	lb	6.18E-01	kg	3.17E-01	9	110
Soda ash[2]	lb	5.59E-01	kg	2.86E-01	5	97
Veneer (purchased)						
Veneer (dry)	lb	8.11E+01	kg	4.16E+01	9	162
Veneer (green)	lb	5.83E+01	kg	2.99E+01	9	210
Water						
Municipal water	gal	6.63E+01	l	2.84E+02	7	97
Well water	gal	5.04E-01	l	2.16E+00	7	149
Recycled water	gal	5.07E+00	l	2.17E+01	4	136
Total water consumption	gal	7.19E+01	l	3.07E+02	8	82
Electricity						
Electricity[3]	kWh	1.28E+02	kWh	1.45E+02	8	27
	MJ	4.62E+02	MJ	5.22E+02		
Fuel						
Hogged fuel (produced)	lb	2.34E+02	kg	1.20E+02	8	97
Hogged fuel (purchased)	lb	8.15E+01	kg	4.18E+01	9	150
Wood waste	lb	4.25E+01	kg	2.18E+01	6	134
Natural gas	ft3	3.96E+01	m3	1.27E+00	9	141
Liquid petroleum gas	gal	4.98E-01	l	2.13E+00	8	43
Gasoline	gal	9.42E-03	l	4.03E-02	9	162
Diesel	gal	4.30E-01	l	1.84E+00	8	72
Packaging						
Cardboard	lb	2.00E-01	kg	1.02E-01	7	85
Steel strapping	lb	2.94E-02	kg	1.51E-02	6	118
Plastic strapping	lb	1.57E-01	kg	8.04E-02	5	102

[1]All materials are given as oven-dry or solid weight.

[2]These material were not included in the LCI analysis based on the 2 percent exclusion rule.

[3]One outlier identified and excluded in production-weighted industry average value.

Table 8. Inputs gate-to-gate for softwood plywood in the SE

Materials[1]	Unit	Quantity per MSF 3/8 inch	Unit	Quantity per m^3	Mills, reporting a value (n)	Weighted Coefficient of Variation (%)
Roundwood	ft3	7.64E+01	m3	2.44E+00		
	lb	2.13E+03	kg	1.23E+03	8	30
Bark	lb	2.08E+02	kg	1.07E+02	8	87
Phenol-formaldehyde resin[2]	lb	2.86E+01	kg	1.47E+01	7	49
Extender and fillers[3]	lb	5.07E+00	kg	2.60E+00	5	110
Catalyst[3]	lb	3.25E-01	kg	1.67E-01	3	120
Soda ash[3]	lb	8.93E-01	kg	4.58E-01	2	117
Veneer (purchased)						
Veneer (dry)	lb	1.88E+01	kg	9.64E+00	8	136
Veneer (green)	lb	6.61E+00	kg	3.39E+00	8	205
Water						
Municipal water	gal	6.58E+01	l	2.81E+02	8	145
Well water	gal	1.50E+01	l	6.43E+01	8	856
Recycled water	gal	1.44E+01	l	6.17E+01	2	300
Total water consumption[4]	gal	9.52E+01	l	4.07E+02	8	73
Electricity						
Electricity[5]	kWh	1.39E+02	kWh	1.58E+02	7	39
	MJ	5.02E+02	MJ	5.67E+02		
Fuel						
Hogged fuel (produced)	lb	2.87E+02	kg	1.47E+02	8	41
Hogged fuel (purchased)	lb	3.41E+01	kg	1.75E+01	8	106
Wood waste	lb	9.18E+01	kg	4.71E+01	7	183
Natural gas	ft3	8.75E+02	m3	2.80E+01	6	107
Liquid petroleum gas	gal	5.00E-01	l	2.14E+00	8	49
Gasoline	gal	2.01E-02	l	8.58E-02	8	56
Diesel	gal	2.88E-01	l	1.23E+00	8	80
Packaging						
Cardboard	lb	5.36E-03	kg	2.75E-03	2	373
Plastic wrapping	lb	9.45E-03	kg	4.85E-03	2	587
Steel strapping	lb	1.32E-02	kg	6.76E-03	3	412
Plastic strapping	lb	8.98E-03	kg	4.60E-03	2	334

[1]All materials are given as oven-dry or solid weight.

[2]One mill stated the PF amount is a trade secret.

[3]These material were not included in the LCI analysis based on the 2 percent exclusion rule.

[4]One outlier identified and excluded in production-weighted industry average value.

[5]One outlier identified and excluded in production-weighted industry average value.

Table 9. Output materials gate-to-gate for softwood plywood in the PNW

Output Materials	Unit	Quantity per MSF 3/8 inch	Unit	Quantity per m^3	Mills, reporting a value (n)	Weighted Coefficient of Variation (%)
Product						
Plywood[1]	lb	8.93E+02	kg	4.58E+02		
Co-products						
Bark	lb	2.19E+02	kg	1.12E+02	7	133
Saw dust	lb	1.59E+01	kg	8.14E+00	6	154
Peeler core	lb	1.40E+02	kg	7.18E+01	5	70
Veneer downfall	lb	7.49E+00	kg	3.84E+00	3	306
Material						
Wood Waste	lb	2.64E+01	kg	1.35E+01	7	144
Ash	lb	1.22E+01	kg	6.27E+00	7	111

[1]Plywood density is based on weighted density of wood species mix (dry) and 80 percent of resin, filler, catalyst and soda ash. The 20 percent less of the resin formula is based on the mass loss in the production process and during the condensation reaction in the curing process (Wilson & Sakimoto, 2004).

Table 10. Output materials gate-to-gate for softwood plywood in the SE

Output Materials	Unit	Quantity per MSF 3/8 inch	Unit	Quantity per m^3	Mills, reporting a value (n)	Weighted Coefficient of Variation (%)
Product						
Plywood[1]	lb	1.01E+03	kg	5.17E+02		
Co-products						
Bark	lb	2.08E+02	kg	1.07E+02	8	104
Saw dust	lb	1.84E+01	kg	9.45E+00	4	162
Peeler core	lb	2.54E+02	kg	1.30E+02	6	65
Veneer downfall	lb	not tracked	kg	not tracked	-	-
Material						
Wood Waste	lb	5.10E+01	kg	2.61E+01	7	116
Ash	lb	2.45E+01	kg	1.25E+01	8	37

[1]Plywood density is based on weighted density of wood species mix (dry) and 80 percent of resin, filler, catalyst and soda ash. The 20 percent less of the resin formula is based on the mass loss in the production process and during the condensation reaction in the curing process (Wilson & Sakimoto, 2004).

The difference in roundwood input between the PNW and SE region (58.46 ft^3 versus 76.41 ft^3 per MSF 3/8 inch) is caused by two factors. In the PNW region, one of the nine surveyed mills reported the usage of purchased veneer only. In the SE region two of the eight surveyed mills reported twice the amount of veneer production than needed for their reported plywood output. The analysis without those three mills resulted to a roundwood input of 67.17 ft^3 and 66.97 ft^3 per MSF 3/8 inch in the PNW and SE regions respectively.

Wood Mass Balance

To verify the reported amounts of inputs and outputs, wood mass balances for both regions were conducted (Tables 11, 12).

Table 11. Wood mass balance for PNW region

Wood Mass Balance[1]	Unit	Quantity per MSF 3/8 inch	Unit	Quantity per m^3
Input				
Roundwood (logs)	lb	1.63E+03	kg	8.37E+02
Purchased veneer (dry)	lb	8.11E+01	kg	4.16E+01
Purchased veneer (green)	lb	5.83E+01	kg	2.99E+01
Total	lb	1.77E+03	kg	9.08E+02
Output				
Plywood[2]	lb	8.70E+02	kg	4.46E+02
Hogged fuel	lb	2.54E+02	kg	1.30E+02
Peeler core	lb	1.40E+02	kg	7.18E+01
Clippings (green)	lb	1.67E+02	kg	8.56E+01
Veneer downfall	lb	7.49E+00	kg	3.84E+00
Panel trim	lb	6.85E+01	kg	3.51E+01
Sawdust	lb	1.59E+01	kg	8.14E+00
Wood waste boiler/ Ash	lb	1.22E+01	kg	6.27E+00
Wood waste	lb	2.64E+01	kg	1.35E+01
Sold veneer (dry)	lb	4.17E+01	kg	2.14E+01
Lay up scrap	lb	1.11E+01	kg	5.66E+00
Unaccounted wood	lb	1.57E+02	kg	8.06E+01
Total	lb	1.77E+03	kg	9.08E+02

[1]All weights are on an oven-dry basis.

[2]Plywood density is based on weighted density of wood species mix (dry).

Table 12. Wood mass balance for the SE region

Wood Mass Balance[1]	Unit	Quantity per MSF 3/8 inch	Unit	Quantity per m^3
Input				
Roundwood (logs)	lb	2.13E+03	kg	1.09E+03
Purchased veneer (dry)	lb	1.88E+01	kg	9.64E+00
Purchased veneer (green)	lb	6.61E+00	kg	3.39E+00
Total	lb	2.16E+03	kg	1.11E+03
Output				
Plywood[2]	lb	9.81E+02	kg	5.03E+02
Hogged fuel	lb	2.87E+02	kg	1.47E+02
Peeler core	lb	2.54E+02	kg	1.30E+02
Clippings (green)	lb	1.64E+02	kg	8.39E+01
Veneer downfall[3]	lb		kg	
Panel trim	lb	1.02E+02	kg	5.22E+01
Sawdust	lb	1.84E+01	kg	9.45E+00
Wood waste boiler/ Ash	lb	2.45E+01	kg	1.25E+01
Wood waste	lb	5.10E+01	kg	2.61E+01
Sold veneer (dry)	lb	2.73E+02	kg	1.40E+02
Lay up scrap[3]	lb		kg	
Unaccounted wood	lb	4.35E+00	kg	2.23E+00
Total	lb	2.16E+03	kg	1.11E+03

[1]All weights are on an oven-dry basis.

[2]Plywood density is based on weighted density of wood species mix (dry).

[3]Not individually tracked by any participating mill in the SE region (included in Hogged fuel).

The ‘Unaccounted wood’ describes output differences of the reported material input and output. The differences of 9 and 2% for the PNW and SE region can be caused by different MC, scaling techniques or by incorrect estimations by survey respondents.

Product Yield

The surveyed plywood mills had a wood recovery of 49 and 45% for the PNW and SE regions, respectively. This percentage was calculated based on the amount of roundwood and veneer input and the output of plywood. In a holistic yield calculation, the amount of ‘sold veneer (dry)’should be included. This reveals a total wood recovery of the surveyed mills in the PNW and SE regions of 51 and 58%, respectively. Trading activities of sawn lumber were excluded by subtracting the reported amounts from the input materials.

Manufacturing Energy Summary

The energy need for the softwood plywood manufacturing process is provided by electricity, wood-based co-products such as bark, hogged fuel, fines and trimmings, and fuels such natural gas, liquid propane gas, diesel and gasoline.

The plywood mills in the PNW and SE documented an electricity use of 128.43 and 139.41 kWh, respectively per MSF 3/8 inch basis. The electricity usage was allocated to the six production stages (Tables 13, 14).

Table 13. Electricity allocation to the production stages in the PNW region

Production Stage	Survey[1] (%)	Allocation		
		(%)[2]	kWh per MSF 3/8 inch	MJ per m^3
Debarking	11.24	13.60	17.46	71.05
Conditioning	12.26	14.62	18.78	76.38
Peeling and Clipping	13.37	15.73	20.20	82.18
Veneer Drying	29.79	32.15	41.29	167.97
Layup and Pressing	15.62	17.98	23.09	93.94
Trimming and Sawing	3.56	5.92	7.60	30.93
Overhead[3]	14.16			
Total	100.00	100.00	128.43	522.45

[1]Allocation on production steps are based on documentation by nine mills.

[2]Weighted allocation of "overhead" electrical load to all production stages.

[3]Overhead includes electricity usage of emission control devices because the energy usage was only documented by one mill.

Table 14. Electricity allocation to the production stages in the SE region

Production Stage	Survey[1] (%)	Allocation		
		(%)[2]	kWh per MSF 3/8 inch	MJ per m^3
Debarking	9.12	11.49	16.02	65.16
Conditioning	10.94	13.31	18.56	75.48
Peeling and Clipping	19.77	22.14	30.86	125.56
Veneer Drying	28.55	30.92	43.10	175.35
Layup and Pressing	14.37	16.74	23.34	94.93
Trimming and Sawing	3.03	5.40	7.53	30.62
Overhead[3]	14.22			
Total	100.00	100.00	139.41	567.11

[1]Allocation on production steps are based on documentation by two mills.

[2]Weighted allocation of "overhead" electrical load to all production stages.

[3]Overhead includes electricity usage of emission control devices because the energy useage was only documented by one of eight mills.

In both regions the veneer peeling and clipping, drying, layup and pressing were reported as the most electricity-intensive processes in the production chain.

The mills reported a total thermal energy need of 2.44E+03 MJ/ m^3 and 3.80E+03 MJ/ m^3 in the PNW (Table 15) and SE (Table 16) regions, respectively. The total thermal energy need was allocated to three production steps: conditioning, drying and pressing.

Table 15. Thermal energy allocation in the PNW region

Fuel Type	Conditioning MJ/m^3	Drying MJ/m^3	Pressing MJ/m^3	Total MJ/m^3	Percent %
Wood fuel[1]	2.31E+02	1.80E+03	3.53E+02	2.39E+03	98
Natural gas[2]	5.35E+00	4.17E+01	8.17E+00	5.52E+01	2
Total	2.37E+02	1.84E+03	3.61E+02	2.44E+03	100
Percent[3] %	9.7	75.5	14.8	100	

[1]Includes hogged fuel self generated and purchased, saw dust, panel trim and veneer downfall.
Energy content 20.93 MJ/kg (Puettmann et al., 2014) 67% efficiency (Wilson et al., 2004)

[2]Energy content natural gas 54.45 MJ/kg (Puettmann et al., 2014), 80% efficiency (Wilson et al., 2004)

[3]Allocation according (Wilson et al., 2004)

Table 16. Thermal energy allocation in the SE region

Fuel Type	Conditioning MJ/m³	Drying MJ/m³	Pressing MJ/m³	Total MJ/m³	Percent %
Wood fuel[1]	2.58E+02	1.99E+03	3.35E+02	2.58E+03	68
Natural gas[2]	1.22E+02	9.39E+02	1.59E+02	1.22E+03	32
Total	3.80E+02	2.93E+03	4.94E+02	3.80E+03	100
Percent[3] %	10	77	13	100	

[1]Includes hogged fuel self generated and purchased, saw dust, panel trim and veneer downfall. Energy content 20.93 MJ/kg (Puettmann et al., 2014) 67% efficiency (Wilson et al., 2004)

[2]Energy content natural gas 54.45 MJ/kg (Puettmann et al., 2014), 80% efficiency (Wilson et al., 2004)

[3]Allocation according (Wilson et al., 2004)

The difference in the required thermal energy between the PNW and SE regions is caused by three mills. In the PNW, one of the nine responding mills reported the usage of exclusively purchased veneer for the plywood manufacturing process. The use of dried veneer reduces the thermal on-site energy consumption drastically because the drying process requires more than 70% of the total thermal energy in the manufacturing process. In the SE region, two of the responding mills reported twice the amount of veneer production than needed for their reported plywood output.

The calculation of the total energy use on-site (Tables 17, 18) included renewable, non-renewable energy sources and electricity use. For the energy calculation, the higher heating value (HHV) was used. These calculations exclude energy losses caused by conversions and represent the potential energy input per functional unit.

Table 17. Fuel and electricity energy on mill site in the PNW region

Fuel Type[1]	BTU per MSF 3/8 inch	MJ per m^3
Renewable fuel use		
Wood fuel[2]	2.99E+06	3.56E+03
Non-renewable fuel use		
Diesel	6.79E+04	8.10E+01
Liquid petroleum gas	9.74E+04	1.16E+02
Natural gas[3]	4.63E+04	5.52E+01
Electricity use		
Electricity	4.38E+05	5.22E+02
Total	3.64E+06	4.34E+03

[1]Energy calculation based on HHV in units of MJ/kg for liquid petroleum gas 54.05, natural gas 54.45, diesel 44.0, wood oven-dry 20.9. Electricity was calculated with 3.6 MJ/kWh. (Puettmann, et al., 2014)(Wilson, et al., 2004).

[2]Includes dry wood material such as hogged fuel self-generated and purchased, saw dust, panel trim and veneer downfall. Total amount of 332.49 lb/ MSF (170.42 kg/m^3) reported as thermal energy source.

[3]Total natural gas usage includes emission control devices (ECDs).

Table 18. Fuel and electricity energy on mill site in the SE region

Fuel Type[1]	BTU per MSF 3/8 inch	MJ per m^3
Renewable fuel use		
Wood fuel[2]	3.23E+06	3.85E+03
Non-renewable fuel use		
Diesel	4.55E+04	5.42E+01
Liquid petroleum gas	9.76E+04	1.16E+02
Natural gas[3]	4.63E+04	5.52E+01
Electricity use		
Electricity	4.76E+05	5.67E+02
Total	3.89E+06	4.64E+03

[1]Energy calculation based on HHV in units of MJ/kg for liquid petroleum gas 54.05, natural gas 54.45, diesel 44.0, wood oven-dry 20.9. Electricity was calculated with 3.6 MJ/kWh. (Puettmann, et al., 2014) (Wilson, et al., 2004).

[2]Includes dry wood material such as hogged fuel self-generated and purchased, sawdust, panel trim and veneer downfall. Total amount of 358.84 lb/ MSF (183.93 kg/m^3) reported as thermal energy source.

[3]Total natural gas usage includes emission control devices (ECDs).

Manufacturing Emission Summary

The provided values for the on-site air emissions were production-weighted (Tables 19, 21) and allocated to the reported contributing production steps (Tables 20, 22).

Table 19. Reported on-site air emissions in the PNW region

Emissions[1]	Unit	Quantity per MSF 3/8 inch	Unit	Quantity per m^3	Mills, reporting a value (n)	Weighted Coefficient of Variation (%)
Acetaldehyde	lb	3.16E-02	kg	1.62E-02	8	132
Acetone	lb	2.17E-02	kg	1.11E-02	1	
Acrolein	lb	7.05E-03	kg	3.61E-03	4	87
CH_4	lb	2.56E+02	kg	1.31E+02	7	522
CO	lb	3.51E+00	kg	1.80E+00	8	109
CO_2	lb	6.50E+02	kg	3.33E+02	8	57
Dust	lb	1.97E-01	kg	1.01E-01	2	139
Formaldehyde	lb	1.74E-02	kg	8.90E-03	8	49
Methanol	lb	8.19E-02	kg	4.20E-02	8	58
NOx	lb	6.60E-01	kg	3.38E-01	8	76
Particulate, PM 2.5	lb	3.60E-01	kg	1.85E-01	7	104
Particulate, PM 10	lb	4.81E-01	kg	2.47E-01	9	126
Phenol	lb	1.13E-03	kg	5.81E-04	4	91
Propionaldehyde	lb	9.61E-03	kg	4.92E-03	1	
SO_2	lb	7.09E-02	kg	3.63E-02	8	65
VOC	lb	3.32E-01	kg	1.70E-01	9	62

[1]Emission values based on survey results (include estimated, measured and permited values).

Table 20. On-site air emission allocation to the production steps in the PNW region

Emissions[1]	Allocation on production steps lb per MSF 3/8 inch			
	Heat Generation Boiler	Veneer Drying	Layup and Pressing	Trimming and Sawing
Acetaldehyde	7.27E-03	1.42E-02	8.12E-03	2.01E-03
Acetone	0.00E+00	1.65E-02	4.64E-03	5.63E-04
Acrolein	2.35E-03	2.35E-03	2.35E-03	0.00E+00
CH_4	1.76E+02	8.02E+01	0.00E+00	0.00E+00
CO	2.83E+00	6.73E-01	0.00E+00	0.00E+00
CO_2	5.27E+02	1.23E+02	0.00E+00	0.00E+00
Dust	1.45E-02	1.80E-02	9.43E-02	6.99E-02
Formaldehyde	8.55E-03	3.25E-03	4.47E-03	1.09E-03
Methanol	8.69E-03	1.44E-02	3.75E-02	2.13E-02
NOx	4.78E-01	1.82E-01	0.00E+00	0.00E+00
Particulate, PM 2.5	1.32E-01	8.79E-02	9.49E-02	4.54E-02
Particulate, PM 10	1.70E-01	1.13E-01	1.36E-01	6.29E-02
Phenol	1.47E-04	1.93E-04	3.54E-04	4.40E-04
Propionaldehyde	3.21E-03	2.54E-03	3.85E-03	0.00E+00
SO_2	5.61E-02	1.48E-02	0.00E+00	0.00E+00
VOC	1.09E-01	5.96E-02	1.36E-01	2.74E-02

[1]Emission allocation based on survey results.

Table 21. Reported on-site air emissions in the SE region

Emissions[1]	Unit	Quantity per MSF 3/8 inch	Unit	Quantity per m^3	Mills, reporting a value (n)	Weighted Coefficient of Variation (%)
Acetaldehyde	lb	4.50E-02	kg	2.30E-02	6	113
Acrolein	lb	1.32E-02	kg	6.79E-03	4	96
Benzene	lb	4.26E-02	kg	2.18E-02	1	
CH_4	lb	1.03E-01	kg	5.27E-02	1	
CO	lb	5.73E+00	kg	2.94E+00	7	91
CO_2	lb	2.41E+02	kg	1.24E+02	3	172
Dust	lb	1.97E+00	kg	1.01E+00	1	
Formaldehyde	lb	6.04E-02	kg	3.09E-02	5	92
Methanol	lb	1.47E-01	kg	7.53E-02	6	73
NO_x	lb	8.89E-01	kg	4.55E-01	7	74
Particulate, PM 2.5	lb	1.02E+00	kg	5.24E-01	5	78
Particulate, PM10	lb	1.17E+00	kg	6.02E-01	7	67
Phenol	lb	9.51E-03	kg	4.87E-03	4	86
Propionaldehyde	lb	1.00E-03	kg	5.14E-04	5	136
SO_2	lb	8.71E-02	kg	4.47E-02	6	77
VOC	lb	1.07E+00	kg	5.46E-01	6	75

[1]Emission values based on survey results (include estimated, measured and permited values). Acetone was not reported in the SE.

Table 22. On-site air emission allocation to the production steps in the SE region

Emissions[1]	Allocation on production steps lb per MSF 3/8 inch			
	Heat Generation Boiler	Veneer Drying	Layup and Pressing	Trimming and Sawing
Acetaldehyde	2.87E-03	3.26E-02	8.57E-03	8.93E-04
Acrolein	7.27E-03	2.40E-03	3.57E-03	0.00E+00
Benzene	4.26E-02	0.00E+00	0.00E+00	0.00E+00
CH_4	1.00E-01	2.57E-03	0.00E+00	0.00E+00
CO	5.32E+00	4.04E-01	9.96E-03	0.00E+00
CO_2	2.33E+02	8.44E+00	0.00E+00	0.00E+00
Dust	1.28E+00	1.54E-01	9.22E-02	4.40E-01
Formaldehyde	1.75E-02	3.12E-02	1.08E-02	9.40E-04
Methanol	3.55E-03	5.56E-02	8.55E-02	2.24E-03
NOx	7.33E-01	1.56E-01	0.00E+00	0.00E+00
Particulate, PM 2.5	7.95E-01	1.04E-01	5.52E-02	6.79E-02
Particulate, PM 10	8.71E-01	1.60E-01	7.74E-02	6.62E-02
Phenol	2.35E-03	4.23E-03	1.93E-03	1.01E-03
Propionaldehyde	1.60E-04	7.23E-04	1.20E-04	0.00E+00
SO_2	8.53E-02	1.86E-03	0.00E+00	0.00E+00
VOC	1.72E-01	4.49E-01	3.48E-01	9.78E-02

[1]Emission allocation based on survey results.

According to the allocation to the individual production steps the conditioning and drying process contribute the most emissions in both regions. These emissions are caused by the thermal energy production through boiler heating systems, which are providing hot water or steam for these processes and emission control devices.

Three mills in the PNW reported a recycle procedure of the exhaust air from the dryer towards the boiler system, which potentially contributed to the carbon dioxide (CO_2) and Methane (CH4) share allocated to the drying procedure. CO_2 and CH_4 are commonly reported to be emitted during the thermal combustion of wood but not in the drying process (J. B. Wilson et al., 2004).

The used emission control devices are regenerative thermal oxidizers (RTOs) for the reduction of volatile organic compounds (VOC's) and electrostatic precipitators (ESPs) for the removal of particulate matter or particle pollution (PM). The usage of RTOs can result into the removal rate of more than 99.9% of VOCs, but releases nitrogen oxides compounds by burning natural gas or liquefied petroleum gas. NO_x potentially increases ozone levels similar to the emission of VOC's. ESPs are used to collect PM pollutions but are not effective in reducing VOC's or HAP emissions (Milota, 2000). The surveyed mills in the PNW and SE reported the installation of five RTOs and two ESPs between 2000 and 2012 in each region. The reported variation within the data set for the production year 2012 for example, 74% CV_w for NO_x emissions and the lack of reporting of estimates of error in the previous study do not allow an analysis of whether the use of these additional ECDs resulted into lower emissions per functional unit.

Life Cycle Impact Assessment

The considered life stages include the forestry operations (raw material acquisition stage) and the production process of plywood (manufacturing stage). Therefore, this assessment is referenced as a cradle-to-gate assessment. For primary data, the reported production-weighted values of the LCI for the production year 2012 within the gate-to-gate system boundaries were used. The secondary data included the forestry operations, specific electricity, resin (J.B. Wilson, 2009) and fossil fuel production. The electricity data were regional-specific. The data were assessed from USLCI and Ecoinvent databases with the SimaPro 8.0 software an LCA software package, and modelled with TRACI 2.1 V1.01/US 2008 method (Puettmann et al., 2012). This method excludes emission released in the combustion process of woody materials. Other emissions such as methane or nitrogen oxides are included in the calculation of the GWP (Bare, 2009).

The SimaPro calculation model was structured as a unit process instead of a ‘black box’ model, which allows users of the data base model to separate between the production of dry veneer and the softwood plywood production. Additionally in this model building approach, a ‘generic’ wood boiler module, which covers the on-site thermal energy production of wood processing companies, was used. This model was developed within the scope of the CORRIM project. To avoid double accounting of emission values caused by the on-site thermal energy production, the boiler model and the allocated emissions for the drying, pressing and trimming production steps were used for the final calculation.

The raw material energy consumption for the production of one cubic meter of softwood plywood in the PNW (Table 23) and SE (Table 24) region was calculated.

Table 23. Raw material energy consumption for the production of one m^3 softwood plywood in the PNW region

Fuel	Total (kg/m^3)	Forestry operations (kg/m^3)	Plywood production (kg/m^3)
Coal, in ground	2.90E+01	2.90E+01	3.60E-04
Gas, natural, in ground	1.84E+01	1.84E+01	3.23E-04
Oil, crude, in ground	1.04E+01	1.04E+01	6.14E-03
Uranium oxide, in ore	6.14E-04	6.14E-04	8.44E-09
Wood waste	2.21E+02	2.21E+02	0.00E+00

Table 24. Raw material energy consumption for the production of one m^3 softwood plywood in the SE region

Fuel	Total (kg/m^3)	Forestry operations (kg/m^3)	Plywood production (kg/m^3)
Coal, in ground	4.68E+01	4.68E+01	3.66E-04
Gas, natural, in ground	3.04E+01	3.04E+01	1.32E-03
Oil, crude, in ground	1.04E+01	1.03E+01	5.54E-03
Uranium oxide, in ore	1.29E-03	1.29E-03	8.38E-09
Wood waste	1.84E+02	1.84E+02	0.00E+00

According to the Product Category Rules (PCR) for North American Structural and Architectural Wood products the impact categories listed in Table 25 must be reported (FPInnovations, 2011). The results of the LCA of one cubic meter of softwood plywood produced in the PNW and SE regions are shown in Table 26 and Table 27, respectively. The results are allocated to two life cycle stages: forestry operation (raw material extraction stage) and the production of plywood (production stage) within the cradle-to-gate system boundaries.

Table 25. Impact categories required by the PCR

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 potentially resulting in acid rain (acidification)	Calculate total acidifying substances including realeased sulphuric acid, sulphur trioxide, hydrogen chloride, hydrogen fluoride, phosphoric acid, and others. Acidification potential is expressed with kg SO_2-eq. as reference unit.	Acidification
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
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 smog	Calculate total substances that can be photo-chemically oxidized. Smog forming potential of O_3 is used as a reference unit.	Photochemical smog

Table 26. Environmental performance of one m^3 softwood plywood produced in the PNW

Impact category	Unit	Total	Forestry operations	Plywood production
Global warming potential (GWP)	kg CO_2 equiv	1.29E+02	2.06E-02	1.29E+02
Acidification potential	kg SO_2 equiv	1.43E+00	2.83E-04	1.43E+00
Eutrophication potential	kg N equiv	5.02E-02	1.95E-05	5.01E-02
Ozone depletion potential	kg CFC-11 equiv	1.01E-07	9.26E-13	1.01E-07
Smog potential	kg O3 equiv	1.98E+01	8.88E-03	1.98E+01
Total Primary Energy consumption				
Non-renewable fossil	MJ	2.22E+03	2.94E-01	2.22E+03
Non-renewable nuclear	MJ	2.34E+02	3.22E-03	2.34E+02
Renewable (solar, wind, hydroelectric, and geothermal)	MJ	1.47E+02	4.97E-04	1.47E+02
Renewable (biomass)	MJ	4.62E+03	3.03E-06	4.62E+03
Waste generated				
Solid waste	kg	6.28E+00	0.00E+00	6.28E+00

Table 27. Environmental performance of one m³ softwood plywood produced in the SE

Impact category	Unit	Total	Forestry operations	Plywood production
Global warming potential (GWP)	kg CO_2 equiv	1.99E+02	2.13E-02	1.99E+02
Acidification potential	kg SO_2 equiv	2.00E+00	2.87E-04	2.00E+00
Eutrophication potential	kg N equiv	5.67E-02	5.65E-05	5.66E-02
Ozone depletion potential	kg CFC-11 equiv	1.24E-07	1.93E-12	1.24E-07
Smog potential	kg O3 equiv	2.19E+01	8.03E-03	2.19E+01
Total Primary Energy consumption				
Non-renewable fossil	MJ	3.33E+03	3.22E-01	3.33E+03
Non-renewable nuclear	MJ	4.93E+02	3.19E-03	4.93E+02
Renewable (solar, wind, hydroelectric, and geothermal)	MJ	2.95E+01	3.49E-04	2.95E+01
Renewable (biomass)	MJ	3.86E+03	1.83E-08	3.86E+03
Waste generated				
Solid waste	kg	1.25E+01	0.00E+00	1.25E+01

Carbon Balance

The carbon balance was calculated based on the production-weighted LCI results and the upstream processes. The kg CO_2 released by the forestry and manufacturing processes was calculated with the SimaPro software.

The kg CO_2 equivalent stored in the final product was calculated according to the 'CORRIM Guidelines for Performing Life Cycle Inventories on Wood Products' (Puettmann et al., 2014). The carbon content of the wood species (Birdsey, 1992) was weighted and showed a CO_2 uptake of 51 and 53% for the PNW and SE region, respectively. To convert the carbon content of the wood into kg CO_2 equivalent, a factor of 3.664 was used. This factor is based on the molar weights of 12.011 and 15.9994 for carbon and oxygen, respectively (Puettmann et al., 2014) (Table 28, 29).

Table 28. Carbon balance of one m^3 of softwood plywood produced in the PNW

	kg CO_2 equivalent
Released during forestry operations	2.06E-02
Released during manufacturing	1.29E+02
CO_2 equiv. stored in product	8.36E+02

Table 29. Carbon balance of one m^3 of softwood plywood produced in the SE

	kg CO_2 equivalent
Released during forestry operations	2.13E-02
Released during manufacturing	1.99E+02
CO_2 equiv. stored in product	9.76E+02

The 836.38 kg and 975.53 kg CO_2 equivalent stored in one cubic meter of softwood plywood produced in the PNW and SE regions, responding to the carbon sequestration from the atmosphere and has therefore a positive effect on the environment.

Conclusion

The life cycle inventories (LCI) conducted for softwood plywood produced in the PNW and SE regions in the U.S. was within the gate-to-gate system boundaries.

The surveyed mills represented 75% and 34% of the total production in the PNW and SE regions, respectively, in 2012. The provided input and output data were reported as production-weighted values per functional unit of one MSF 3/8 in (0.884 m^3).

The production of softwood plywood in the PNW required 58.46 ft^3 (1,632 lb.) of roundwood and 139 lb. of purchased veneer (81 lb. dry veneer and 58 lb. green veneer) per functional unit (MSF 3/8 in). The total wood recovery of 51% was calculated based on the amount of wood inputs in roundwood and veneer to the output of wood in form of plywood (870 lb.) and sold dry veneer (41.75 lb.). The production of one MSF 3/8 in of softwood plywood required 2.04 million BTUs thermal energy. The production of the thermal energy was covered with 98% wood fuel and 2% natural gas. The allocation of the thermal energy need of the conditioning, drying and pressing process was allocated according to Wilson et al. (2004) because of a lack of reporting by the participating mills. The total electricity consumption was 128 kWh per functional unit and was allocated to following processes; veneer drying (32%), layup and pressing (18%), peeling clipping (16%), conditioning (15%), debarking (13%), and trimming and sawing (6%).

The production of softwood plywood in the SE required 76.41 ft^3 (2,134 lb.) of roundwood and 25 lb. of purchased veneer (19 lb. dry veneer and 6 lb. green veneer) per functional unit (MSF 3/8 in). The total wood recovery 58% was calculated based on the amount of wood inputs in form of roundwood and veneer to the output of wood in form of plywood (981 lb.) and sold dry veneer (273 lb.). The production of one MSF 3/8 in of softwood plywood required 2.88 million BTUs thermal energy. The production of the thermal energy was covered with 75% hogged fuel and 25% natural gas. The allocation of the thermal energy need of the conditioning, drying and pressing process was allocated according to Wilson et al. (2004) because of a lack of reporting of the participating mills. The total electricity consumption was 139 kWh per functional unit and was allocated to following processes; veneer drying (31%), peeling and clipping (22%), layup and pressing (17%), conditioning (13%), debarking (11%), and sawing and trimming (5%).

The allocations to the individual production steps provided the basis for conducting a life cycle impact assessment with a unit process structure. SimaPro 8.0, an LCA software package, running the TRACI 2.1 V1.01/US 2008 method was used to calculate the environmental impact associated with the production of softwood plywood in both regions. Primary data in form of the LCI figures and secondary data for the forestry, energy and other input material production were used. The results for the softwood plywood production in the PNW show a global warming potential of 1.29E+02 kg carbon dioxide equivalent, acidification potential of 1.43E+00 kg sulfur dioxide equivalent, eutrophication potential of 5.02E-02 kg nitrogen equivalent, ozone depletion of 1.01E-07 kg trichlorofluoromethane equivalent and smog potential of 1.98E+01 kg ozone equivalent. Softwood plywood produced in the PNW stores 1631 lb. of CO2 equivalent per m^3.

The results for the softwood plywood production in the SE show a global warming potential of 1.99E+02 kg carbon dioxide equivalent, acidification potential of 2.00E+00 kg sulfur dioxide equivalent, eutrophication potential of 5.67E-02 kg nitrogen equivalent, ozone depletion of 1.24E-07 kg trichlorofluoromethane equivalent and smog potential of 2.19E+01 kg ozone equivalent. Softwood plywood produced in the SE stores 1,903 lb. of CO_2 equivalent per m^3.

The comparison between the two product life stages: raw material extraction and the production process shows that in both regions the production process contributes the main environmental burdens in the five documented impact categories.

The calculated potential impacts should contribute to the update of the environmental product declaration of softwood plywood produced in the U.S. and should allow a fair comparison with competing products.

CHAPTER 2 - LIFE CYCLE INVENTORY OF ORIENTED STRAND BOARD PRODUCTION IN THE UNITED STATES

Abstract

This study presents the collection and preparation of the life cycle inventory (LCI) data for oriented strand board (OSB) produced in the U.S. OSB producers were invited to provide input and output data for the production year 2012. The surveyed mills represent 33.39% of the total production output in the survey year.

Production-weighted average values of the collected input and output data were determined, based on the functional unit of one MSF 3/8 inch basis (0.885 m^3) OSB. The collected primary data cover the environmental burdens within the gate-to-gate system boundaries. The life cycle impact assessment (LCIA) from cradle-to- gate required secondary data for the forestry operations, electricity, resin and thermal energy production. These data were assessed from the USLCI and Ecoinvent databases using with the SimaPro 8.0, an LCA software package, and modelled by using the 'Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts' (TRACI 2.1 V1.01/US 2008) method (Bare, 2009).

The results of this study will contribute to the update of the environmental product declaration (EPD) for OSB and will assure compliance with the data quality requirements of the relevant classification standard the Product Category Rule (PCR) for North American Structural and Architectural Wood Products (FPInnovations, 2011).

Introduction

Oriented Strand Board (OSB) is an engineered, wood-based panel building product. OSB is made of layers of wood ‘strands’, which are thin (mm) but a few cm wide and longer (3x) than they are wide. These strands are oriented along their long axis to provide optimal product properties in the panel. The outer layers consist of strands aligned in the long direction of the panel (typically 4’ x 8’, while the middle layer includes smaller strands that are oriented at 90 degrees to the outer layers. OSB is commonly used as wall, roof, and floor sheathing in the residential and commercial building sector (FPL, 2010) (Kline, 2004).

Figure 4. OSB (NPI, 2014)

Although OSB is produced in different grades and thicknesses, a commonly-used unit of volume in the industry is one thousand square feet (MSF) on a 3/8 inch basis (0.885 cubic meters) (Kline, 2004).

The aim of this project was to provide representative values for the inputs required for the production of OSB in the U.S. for the production year 2012 and the associated outputs and emissions. This study collected primary data within the system boundaries of the production process (gate-to-gate). For the holistic evaluation of the environmental impacts of the cradle-to-gate process, the TRACI 2.1 V1.01/US 2008 model (Bare, 2009) was used, drawing on preexisting data for electricity, resin and wood production.

For the primary data collection, twenty-five OSB mills in the U.S. were invited to contribute detailed production data for the assessment. The survey instrument was based on the used one in a prior study (Kline, 2004) that was updated for current conditions. Of the contacted companies eight mills (32%) provided the required input and output data for the assessment. The resulting data were weight-averaged by mill production volume and allowed a detailed analysis of the environmental impacts associated with the OSB production. The results will contribute to the development of the environmental product declaration (EPD) of this wood-based building product.

The responding mills were located in the Southeast and Northeast regions and produced 3.69 billion square feet on a 3/8 inch basis, which represents 33% of the total OSB production (11.04 billion square feet 3/8 inch basis) in the U.S. (APA, 2013a). The individual mills had a production output of about 300,000 to 650,000 MSF 3/8 inch basis and the mills ages ranged from 8 to 32 years. The mills employed 152 persons based on the production-weighted average.

Manufacturing Process of OSB

The OSB manufacturing process can be described as eight main steps (Table 30).

Table 30. Description of the production flow of OSB and the associated inputs and outputs of each step

Production Process		Inputs	Outputs
1. Debarking	Bucking and sorting the logs on the log yard Debarking of the logs	• Round timber • Diesel for log loaders • Electricity	• Debarked logs • Bark • Wood residues • Water emissions caused by water runoff from the log yard
2. Flaking	The flaking process strives to produce uniform thick strands, which are up to 6 inches long and about 1 inch wide	• Debarked logs • Electricity	• Green flakes
3. Drying	Green flakes will be dried to 4-8 percent MC. The drying process requires thermal energy, which will be commonly produced by burning wood by-products and fossil energy sources	• Flakes (green) • Wood fuel: Bark, Screening fines, OSB trimmings and other Wood residues • Natural gas	• Flakes (dry) • Air emissions • Airborne particles • Volatile organic compounds (VOCs)
4. Screening	The screening process removes fines and too small flakes from the material flow for subsequent manufacturing	• Flakes (dry) • Electricity	• Appropriate sized flakes • Fines and particles which are used as fuel for the drying and heating press oil
5. Blending	In the blending process strands are blended with resin binders and wax	• Appropriate sized flakes • Phenol Formaldehyde (PF) • Methylene Diphenyl Diioscyanate (MDI) • Wax • Electricity	• Blended flakes
6. Forming	The blended flakes are formed to a OSB mat with cross-directional layers in the forming line	• Blended strands • Electricity	• Formed OSB mat • Air emissions VOCs and Hazardous air pollutants (HAPs)
7. Pressing	The formed OSB mat is carried in a muliple opening or continous press where under the comination of pressure and tempreture a rigid and dense board is produced	• Formed OSB mat • Thermal energy • Electricity	• OSB • Air emissions VOCs, HAPs and formaldehyde emissions
8. Finishing	The produced OSB boards are cooled, sawn to appropriate size, grade stamped, stacked in bundles, and packaged for shipping	• OSB • Electricity • Fuel for forklifts	• OSB • By-products such as trimmings, sawdust, sander dust and rejected boards are used as heating fuel or sold • Air emssions VOCs and HAPs

According to the designated system boundaries (gate-to-gate), the following inputs, outputs and main material flows were considered (Figure 5). The thermal energy production, the thermal oil heater system, emission control (ECD) and resin wax production was considered as additional sub processes within the system boundary.

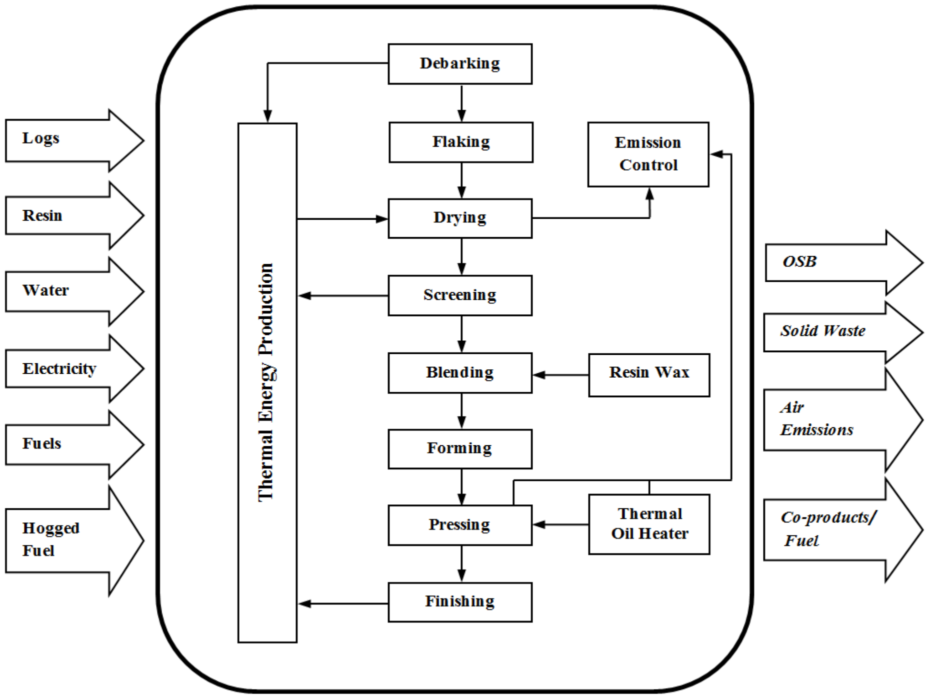

Figure 5. System boundary and sub-unit processes of OSB production

Materials Flow

The materials considered for the LCI analysis were categorized in three main groups (Table 31).

Table 31. Input materials, co-products and products in the OSB manufacturing process

Input Materials	Co-products	Products
Logs	Bark (green)	OSB
PF resin	Chips (green)	
MDI resin	Cut-offs (dry)	
Wax	Sawdust (dry)	
Water		
Packaging Material		

Transportation

The participating OSB mills reported transportation data for their raw materials by both distance (one way) and mode (truck or train) (Table 32).

Table 32. Delivery distance of input materials for OSB production

Material	Transportation Method	Delivery Distance (miles)[1]	Delivery Distance (km)[1]	Mills, reporting a value (n)	Weighted Coefficient of Variation (%)
Logs (roundwood)	Truck	59.85	96.32	7	43
Logs (roundwood)	Train	68.00	109.44	1	
Resin[2]	Truck	294.70	474.27	8	82
Resin[2]	Train	1288.00	2072.83	1	

[1]All transportation distances weight averaged and one way.

[2]Weighted average value for PF, MDI and wax delivery.

The transportation distance of hogged fuel, which is an energy source for thermal energy production was assumed to be 40 mile (64.37 km).

Density Calculation

The roundwood input documented by the OSB mills was reported in green short tons. To calculate the wood input, the amount of bark was subtracted and the short tons converted to metric tons. The wood mix was represented for 67% softwood and 33% hardwood. To calculate the volume of the wood input, the species mix was weighted and densities assumed for each species according to the Wood Handbook (2010) (Table 33).

Table 33. Calculation of wood mass from logs for OSB production in the U.S.

Wood Species	Useage acc. Survey (%)	Density[1] (lb/ft³)	Weighted Average Density		Mills, reporting a value[2] (n)
			lb/ft³	kg/m³	
Pine[3]	73.45	31.51	23.14	370.72	7
Aspen	9.20	21.85	2.01	32.19	1
Spruce	1.02	23.10	0.24	3.78	1
Maple	4.05	30.59	1.24	19.84	2
Birch	1.02	34.33	0.35	5.62	1
Basswood	0.51	19.98	0.10	1.64	1
Oak	2.89	32.46	0.94	15.01	2
Poplar	5.62	28.72	1.61	25.86	2
Cherry	0.48	29.34	0.14	2.23	1
Beech	1.77	34.96	0.62	9.90	1
Total	100.00		30.39	486.78	

[1]Density according Wood Handbook 2010.

[2]Wood mix percentages were provided from seven mills.

[3]50% loblolly pine and 50% slash pine assumed.

Assumptions

The data collection, analysis and assumptions followed protocols as defined in the 'CORRIM Guidelines for Performing Life Cycle Inventories on Wood Products' (Puettmann et al., 2014). Additional considerations included:

- All survey data contributed by the eight participating OSB plants were production-weighted in comparison to the total surveyed production for the year 2012;

- The OSB board density depends on the species used and the grades, which require certain mechanical properties according to the standards. The density of the OSB boards was assumed to be 39.5 lb./ft3 (632.73 kg/m3). This density was based on informal discussion with mill personnel of three surveyed mills;

- For bark, hogged fuel, wood and wood waste (green) 50% moisture content (MC) on a dry basis was assumed. For sawdust and dry wood waste, 7% MC on a dry basis was assumed;

- The resin components were converted to the solid content based on the percentages reported in the surveys;

- The allocation of the fossil energy source is based on the information provided by the mills:

- 100% of the liquid propane gas (LPG) was used for mobile equipment and was assigned to the finishing process steps;

- 100% of diesel fuel was allocated for mobile equipment on the log yard for transporting and hauling the logs;

- 95% of the natural gas usage is allocated to the emission control and 5% for the pressing process to heat the needed thermo oil in the fuel cells;

- Unaccounted wood mass of 0.11% was established by the difference between reported input and output wood material flows (Table 36); since there was a similar weight difference between hogged fuel and bark, much of the difference may have been wood that was hogged for fuel;

- SimaPro 8.0., a software package designed for analyzing the environmental impact of products during their whole life cycle, was used to perform the life cycle analysis. SimaPro 8.0. contains a U.S. database for a number of materials, including paper products, fuels, and chemicals. In this assessment secondary data from the USLCA and EcoInvent database were used to model the LCA scenario.

Data Quality Assessment and Calculation of Inventory Data

The data quality assessment of the reported data included a standardized outlier detection method, the reporting of the sample size as ‘Mills reporting a value (n)’ and the reporting of the variation of the dataset in form of the weighted coefficient of variation (CV_w). These methods are now included in the ‘CORRIM Guidelines for Performing Life Cycle Inventories on Wood Products’. In general, outliers are defined as extreme observations that can have a significant impact on calculated values. In case of the collected survey data, outliers could be values that are incorrectly reported because the true value is not known or the question was misunderstood. JMP Pro 11 statistical software was used to analyze the data set for outliers. The following example (Figure 6), shows the analysis of the reported data for ‘Hogged fuel purchased”.

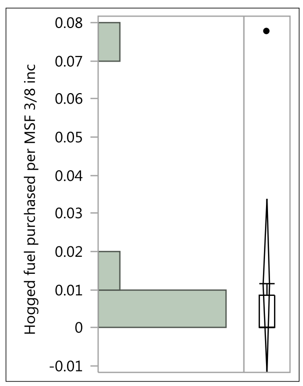

Figure 6. Distribution of reported ‘hogged fuel purchased’ of OSB production in the U.S.

Outlier is shown as dot in the box plot output (Figure 6, right). Hogged fuel describes coarse woody material for the thermal energy production. Two of the eight reporting OSB mills used purchased hogged fuel whereas the others used exclusively hogged fuel generated as a by-product from their own OSB manufacturing process. The indicated outlier was discussed and verified as a correct stated value by the mill personnel and was therefore not excluded of the calculation of the production-weighted average value. The coefficient of variation (CV) describes the variability of the data series by dividing the standard deviation by the mean (Abdi, 2010). To be consistent with the documented production-weighted average values (1), the weighted standard deviation (2) was calculated. The weighted CV_w (3) was calculated and documented for the individual values (NIST, 1996) (Toshkov, 2012).

$$\bar{x}_w = \frac{\sum wx}{\sum w} \quad (1)$$

$$Sd_w = \sqrt{\sum_{i=1}^{N} w_i (x_i - \bar{x}_w)^2 \, x \, \frac{N'}{(N'-1)\sum_{i=1}^{N} w_i}} \quad (2)$$

$$CV_w = \frac{Sd_w}{\bar{x}_w} \quad (3)$$

The description of the data set should provide the basis for statistical analyses of future updates with the production-weighted values of 2012.

Life Cycle Inventory Results

The survey results were compiled to calculate production-weighted average values of the input (Table 34) and output (Table 35) materials associated with the production of one MSF 3/8 inch basis of OSB.

Table 34. Input materials gate-to-gate for OSB

Input Materials[1]	Unit	Quantity per MSF 3/8 inch	Unit	Quantity per m^3	Mills, reporting a value (n)	Weighted Coefficient of Variation (%)
Roundwood	ft3	5.16E+01	m3	1.65E+00		
Wood	lb	1.57E+03	kg	8.04E+02	8	10
Bark	lb	2.15E+02	kg	1.10E+02	8	32
Phenol-formaldehyde resin	lb	2.36E+01	kg	1.21E+01	8	30
Methylene diphenyl diisocyanate resin	lb	1.16E+01	kg	5.95E+00	7	56
Wax	lb	7.34E+00	kg	3.76E+00	8	39
Water						
Municipal water	gal	1.05E+01	l	4.49E+01	3	256
Well water	gal	2.06E+01	l	8.80E+01	5	131
Recycled water	gal	3.12E-01	l	1.33E+00	2	407
Total water consumption	gal	3.14E+01	l	1.34E+02	8	67
Electricity						
Electricity	kWh	1.34E+02	kWh	1.52E+02	8	17
	MJ	4.83E+02	MJ	5.46E+02		
Fuel						
Hogged fuel (produced)	lb	3.32E+02	kg	1.70E+02	8	17
Hogged fuel (purchased)	lb	2.90E+01	kg	1.49E+01	8	215
Wood waste	lb	3.61E+02	kg	1.85E+02	8	117
Natural gas	ft3	6.73E+02	m3	2.15E+01	8	47
Liquid petroleum gas	gal	6.62E-02	l	2.83E-01	7	50
Diesel	gal	9.64E-02	l	4.12E-01	8	71
Gasoline	gal	5.37E-03	l	2.30E-02	7	59
Packaging						
Cardboard	lb	3.43E-01	kg	1.76E-01	5	160
Plastic wrapping	lb	3.17E-02	kg	1.62E-02	2	423
Plastic strapping	lb	4.85E-02	kg	2.49E-02	3	206
Steel strapping	lb	1.13E-02	kg	5.78E-03	2	301

[1]All materials are given as oven-dry or solid weight.

Table 35. Output materials gate-to-gate for OSB

Output Materials	Unit	Quantity per MSF 3/8 inch	Unit	Quantity per m^3	Mills, reporting a value (n)	Weighted Coefficient of Variation (%)
Product						
OSB[1]	lb	1.23E+03	kg	6.33E+02		
Co-products						
Bark	lb	3.78E+01	kg	1.94E+01	8	32
Saw dust	lb	2.18E+01	kg	1.12E+01	4	141
Panel trim	lb	4.96E+00	kg	2.54E+00	2	340
Material						
Wood Waste	lb	2.30E+01	kg	1.18E+01	5	139
Ash	lb	6.54E+00	kg	3.35E+00	7	108

[1]OSB density was assumed based on informative discussions with mill personal.

Wood Mass Balance

To verify the survey information in terms of the wood mass flow through the production chain a wood mass balance was conducted (Table 36). The amount of "unaccounted wood" was 0.11%.

Table 36. Wood mass balance for OSB

Wood Mass Balance[1]	Unit	Quantity per MSF 3/8 inch	Unit	Quantity per m^3
Input				
Roundwood (logs)	lb	1.57E+03	kg	8.04E+02
Hogged fuel (purchased)	lb	2.90E+01	kg	1.49E+01
Total	lb	1.60E+03	kg	8.19E+02
Output				
OSB (wood)[2]	lb	1.19E+03	kg	6.11E+02
Hogged fuel (sold)	lb	3.78E+01	kg	1.94E+01
Hogged fuel (produced)	lb	2.95E+02	kg	1.51E+02
Wood waste (sold)	lb	2.30E+01	kg	1.18E+01
Wood waste (produced)	lb	1.95E+01	kg	1.00E+01
Saw dust	lb	2.18E+01	kg	1.12E+01
Panel trim	lb	4.96E+00	kg	2.54E+00
Wood ash	lb	6.54E+00	kg	3.35E+00
Unaccounted wood	lb	-1.70E+00	kg	-8.71E-01
Total	lb	1.60E+03	kg	8.19E+02

[1]All weights are on an oven-dry basis

[2]Woodmass was calculated based on assumed OSB weight (632.73 kg/m^3) minus 80 percent of total use of resin, filler, catalyst and soda ash. The 20 percent less of the resin formula is based on the mass loss in the production process and during the condensation reaction in the curing process according (Kline, 2004).

Product Yield

The wood recovery in the surveyed OSB plants was 75%. This figure was calculated based on the roundwood input and the output of wood in form of OSB. The production of one MSF 3/8 inch basis OSB required a total roundwood input of 51.62 ft^3 (1.65 m^3) or 1568.66 lb. (804.03 kg) of logs. The weight of the wood input was calculated based on the volume and wood densities (Table 33).

Manufacturing Energy Summary

The energy need for the manufacturing process of OSB is provided in form of electricity, wood-based co-products such as bark, hogged fuel, fines and trimmings, and fossil fuel energy sources such as natural gas, liquid propane gas, diesel and gasoline. The fossil fuel sources were allocated according to the assumptions. The electricity use of 134.12 kWh (545.62 MJ) per produced MSF 3/8 inch basis was allocated to the individual production stages, based on estimates provided by the surveyed mills (Table 37).

Table 37. Electricity allocation to production stages for OSB

Production Stage	Survey (%)	Allocation		
		(%)[1]	kWh per MSF 3/8 inch	MJ per m^3
Debarking	6.90	9.44	12.67	51.52
Flaking	18.36	20.90	28.04	114.05
Drying	5.80	8.34	11.19	45.52
Screening	4.85	7.39	9.92	40.34
Blending	4.70	7.24	9.72	39.52
Forming	5.70	8.24	11.06	44.98
Pressing	16.50	19.04	25.54	103.90
Finishing	4.36	6.90	9.26	37.67
Emission Control[2]	9.94	12.48	16.74	68.11
Overhead	22.89			
Total	100.00	100.00	134.12	545.62

[1]Weighted allocation of overhead electrical load to all production stages

[2]Electricity useage for ECDs based on documentation by two mills

The OSB mills reported a total thermal energy need of 2.57E+03 MJ/ m3. This is based on the production-weighted input values allocated according to the stated usage in the drying and pressing processes (Table 38).

Table 38. Thermal energy allocation to the production stages of OSB

Fuel Type	Drying MJ/m^3	Pressing MJ/m^3	Total MJ/m^3	Percent %
Wood fuel[1]	2.39E+03		2.39E+03	93
Natural gas[2]	1.32E+02	5.51E+01	1.87E+02	7
Total	2.52E+03	5.51E+01	2.57E+03	100
Percent %	98	2	100	

[1]Includes hogged fuel, wood waste, saw dust and panel trim. Energy content 20.93 MJ/kg (Puettmann et al., 2014) 67 percent boiler efficiency (Wilson et al., 2004)
[2]Energy content natural gas 54.45 MJ/m^3 (Puettmann et al., 2014), 80 percent conversion efficiency (Wilson et al., 2004). 80 percent of total natural gas input was reported for Emission control devices (ECD).

The calculation of the total energy use on-site (Table 39) includes renewable, non-renewable energy sources and electricity use. For the energy calculation, the higher heating value (HHV) was used. These calculations exclude energy losses caused by conversions and represent the potential energy input per functional unit.

Table 39. Fuel and electricity energy on mill site for OSB

Fuel Type[1]	BTU per MSF 3/8 inch	MJ per m^3
Renewable fuel use		
Wood fuel[2]	3.07E+06	3.66E+03
Non-renewable fuel use		
Diesel	1.52E+04	1.81E+01
Liquid petroleum gas	1.29E+04	1.54E+01
Natural gas[3]	9.83E+05	1.17E+03
Electricity use		
Electricity	4.58E+05	5.46E+02
Total	4.54E+06	5.41E+03

[1]Energy calculation based on HHV in units of MJ/kg for liquid petroleum gas 54.05, natural gas 54.45, diesel 44.0, wood oven-dry 20.9. Electricity was calculated with 3.6 MJ/kWh. (Puettmann, et al., 2014)(Wilson, et al., 2004).
[2]Hogged fuel 340.83 lb/ MSF (174.68 kg/m^3) reported as thermal energy source.
[3]Total natural gas usage includes emission control devices (ECDs).

Manufacturing Emission Summary

The provided values for the on-site air emission were production-weighted (Table 40) and allocated to contributing production steps (Table 41).

Table 40. Reported on-site air emissions for OSB

Emissions	Unit	Quantity per MSF 3/8 inch	Unit	Quantity per m^3	Mills, reporting a value (n)	Weighted Coefficient of Variation (%)
Acetaldehyde	lb	1.36E-02	kg	6.99E-03	8	98
Acetone	lb	4.12E-03	kg	2.11E-03	4	147
Acrolein	lb	4.00E-03	kg	2.05E-03	7	114
CO	lb	5.61E-01	kg	2.88E-01	8	85
CO_2	lb	6.46E+01	kg	3.31E+01	4	105
Formaldehyde	lb	3.14E-02	kg	1.61E-02	8	58
MDI	lb	1.90E-04	kg	9.75E-05	5	123
Methanol	lb	6.18E-02	kg	3.17E-02	7	90
NO_x	lb	4.86E-01	kg	2.49E-01	8	42
Particulate, PM 2.5	lb	1.41E-01	kg	7.25E-02	7	84
Particulate, PM 10	lb	2.33E-01	kg	1.20E-01	8	38
Phenol	lb	5.20E-03	kg	2.66E-03	6	116
Propionaldehyde	lb	2.18E-03	kg	1.12E-03	7	191
SO_2	lb	5.10E-02	kg	2.62E-02	8	67
VOC	lb	4.97E-01	kg	2.55E-01	8	81

According to the allocation to the individual production steps, the drying process contributes the most emissions. These are caused by the thermal energy production through the direct fired process and by the emission control devices. The eight surveyed OSB mills reported the implementation of three regenerative thermal oxidizers (RTOs) and one electrostatic precipitator (ESP) between 1999 and 2012. The mills stated that the RTOs consume 80% (Table 38) of the total natural gas usage. The ESP (based on information from two mills) consumed about 13% of the total electricity usage. Kline (2004) stated that RTOs are very effective in removing particulate matter (PM), CO and VOCs from process air. Hence the additional energy input results into an overall increase of other greenhouse gases such as CO_2, SO_2, NO_x and methane.

Table 41. On-site air emission allocation to the production steps for OSB

Emissions[1]	Allocation on production steps lb per MSF 3/8 inch		
	Drying	Pressing	Finishing
Acetaldehyde	1.15E-02	2.10E-03	0.00E+00
Acetone	3.06E-03	1.05E-03	0.00E+00
Acrolein	3.29E-03	7.05E-04	0.00E+00
CO	5.02E-01	2.81E-02	3.13E-02
CO_2	4.71E+01	1.75E+01	0.00E+00
Formaldehyde	2.15E-02	6.27E-03	3.56E-03
MDI	8.41E-05	3.98E-05	6.64E-05
Methanol	2.35E-02	1.61E-02	2.22E-02
NO_x	3.82E-01	9.03E-02	1.35E-02
Particulate, PM 2.5	8.99E-02	2.10E-02	3.05E-02
Particulate, PM 10	1.28E-01	5.49E-02	5.00E-02
Phenol	2.33E-03	2.87E-03	0.00E+00
Propionaldehyde	1.23E-03	9.50E-04	0.00E+00
SO_2	4.06E-02	9.96E-03	4.73E-04
VOC	2.39E-01	7.13E-02	1.86E-01

[1]Emission allocation based on survey results.

The reported variation within the data set for the production year 2012 for example, 42% CV_w for NO_x emissions and the lack of estimates of error in the previous study do not allow an analysis of whether the differences are real.

Life Cycle Impact Assessment

A life cycle impact assessment for the production of one m^3 of OSB produced in the U.S. required primary and secondary data. The considered life stages include the forestry operations and the production process of OSB (cradle-to-gate). The reported production-weighted values of the LCI for the production year 2012 within the gate-to-gate system were used as primary data. The secondary data included the forestry operations, electricity, resin and fossil fuel production. These data were combined with the primary data and modelled with SimaPro 8.0, an LCA software package, by using the TRACI 2.1 V1.01/US 2008 model in a ‘black box’ approach. The TRACI 2.1 V1.01/US 2008 method excludes emission released in the combustion process of woody materials. Other emissions such as methane or nitrogen oxides are included in the calculation of the GWP (Puettmann et al., 2014). The ‘black box’ approach has a lack of modeling individual production steps along the production chain. This approach is justified by the absence of final processed goods within the production chain.

The raw material energy consumption for the production of one m^3 OSB was calculated (Table 42).

Table 42. Raw material energy consumption for the production of one m^3 OSB

Fuel	Total (kg/m^3)	Forestry operations (kg/m^3)	OSB production (kg/m^3)
Coal, in ground	4.48E+01	4.18E-01	4.43E+01
Gas, natural, in ground	3.11E+01	0.00E+00	4.96E+00
Oil, crude, in ground	1.11E+01	1.32E+00	9.78E+00
Uranium oxide, in ore	1.27E-03	9.74E-06	1.26E-03
Wood waste	1.85E+02	0.00E+00	1.85E+02

According to the Product Category Rules (PCR) for North American Structural and Architectural Wood products the impact categories listed in Table 43 must be reported (FPInnovations, 2011). The result of the LCA of one cubic meter of OSB is shown in Table 44. The results are allocated to two life cycle stages: forestry operation (raw material extraction stage) and the production of OSB (production stage) within the cradle-to-gate system boundaries.

Table 43. Impact categories required by the PCR

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 potentially resulting in acid rain (acidification)	Calculate total acidifying substances including realeased sulphuric acid, sulphur trioxide, hydrogen chloride, hydrogen fluoride, phosphoric acid, and others. Acidification potential is expressed with kg SO_2-eq. as reference unit.	Acidification
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
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 smog	Calculate total substances that can be photo-chemically oxidized. Smog forming potential of O_3 is used as a reference unit.	Photochemical smog

Table 44. Environmental performance of one m^3 OSB

Impact category	Unit	Total	Forestry operations	OSB production
Global warming potential (GWP)	kg CO_2 equiv	2.07E+02	2.47E+01	1.82E+02
Acidification potential	kg SO_2 equiv	2.12E+00	3.26E-01	1.79E+00
Eutrophication potential	kg N equiv	9.97E-02	5.28E-02	4.69E-02
Ozone depletion potential	kg CFC-11 equiv	6.34E-07	1.92E-09	6.32E-07
Smog potential	kg O3 equiv	2.77E+01	9.41E+00	1.83E+01
Total Primary Energy consumption				
Non-renewable fossil	MJ	3.35E+03	1.34E+02	3.22E+03
Non-renewable nuclear	MJ	4.82E+02	3.71E+00	4.78E+02
Renewable (solar, wind, hydroelectric, and geothermal)	MJ	5.13E+01	4.35E-01	5.09E+01
Renewable (biomass)	MJ	3.88E+03	1.55E-05	3.88E+03
Waste generated				
Solid waste	kg	3.36E+00	0.00E+00	3.36E+00

Carbon Balance

The carbon balance was calculated based on the production-weighted LCI results and the upstream processes. The released kg CO_2 of the forestry and manufacturing procedure was calculated with the SimaPro software. The kg CO_2 equivalent stored in the final product was calculated according to the 'CORRIM Guidelines for Performing Life Cycle Inventories on Wood Products' (Puettmann et al., 2014). The carbon content of the reported species (Birdsey, 1992) was weighted and showed a CO_2 uptake of 51%. To convert the CO_2 uptake into kg CO_2 equivalent the factor 3.664 was used. This factor is based on the molar weight of 12.011 and 15.9994 for carbon and oxygen, respectively (Puettmann et al., 2014) (Table 45).

Table 45. Carbon balance of one m^3 of OSB

	kg CO_2 equivalent
Released during forestry operations	2.47E+01
Released during manufacturing	1.82E+02
CO_2 equiv. stored in product	1.05E+03

The 1053.61 kg CO_2 equivalent stored in one cubic meter OSB contributes to the carbon sequestration from the atmosphere and has therefore a positive effect on the environment.

Conclusion

The conducted life cycle inventory (LCI) for OSB produced in the U.S. was within the gate-to-gate system boundaries. The surveyed mills represented 33% of the total OSB production in the U.S. The provided input and output data were reported as production-weighted values per functional unit of one MSF 3/8 inch (0.884 m^3). The production of OSB in the U.S. required 51.62 ft^3 (1,567 lb.) of roundwood. A wood recovery of 75% was calculated based on the amount of roundwood input to the output of wood in form of OSB (1,192 lb.) per functional unit. The production of one MSF 3/8 in of OSB required 2.17 million BTU's thermal energy, which was provided by with 95% wood fuel and 5% natural gas. The total electricity consumption was 134 kWh per functional unit and was allocated on following production steps; flaking (21%), pressing (19%), debarking (9%), drying (8%), forming (8%), blending (7%), screening (7%), and finishing (7%).

The remaining 12% of electricity was used for the emission control devices (ECD's) such as electrostatic precipitator (ESPs). Gas driven ECD's such as regenerative thermal oxidizers (RTOs) are also the main consumers (80%) of the total reported natural gas.

For the evaluation of the environmental performance within the gradle-to-gate system boundary of OSB produced in the U.S., SimaPro 8.0, an LCA software package was used with the TRACI 2.1 V1.01/US 2008 model (Bare, 2009). The calculation of the environmental impact associated with the production of OSB required primary data in form of the LCI figures and secondary data for the forestry, energy and other input material production. The results of the evaluation of the OSB production in the U.S. shows a global warming potential of 2.07E+02 kg carbon dioxide equivalent, acidification potential of 2.12E+00 kg sulfur dioxide equivalent, eutrophication potential of 9.97E-02 kg nitrogen equivalent, ozone depletion of 6.34E-07 kg trichlorofluoromethane equivalent and smog potential of 2.77E+01 kg ozone equivalent. OSB produced in the U.S. stores 2,056 lb. of CO_2 equivalent per m^3.

The comparison between the two product life stages: raw material extraction and the production process shows that the production process contributes the main environmental burdens in the five documented impact categories.

The calculated potential impacts should contribute to the update of the environmental product declaration of OSB produced in the U.S. and should allow a fair comparison with competing products.

CHAPTER 3 - LIFE CYCLE ASSESSMENT AND ANALYSIS OF THE STRUCTUAL WOOD PANEL INDUSTRIES OVER TIME

Abstract

This study investigates the use of successive life cycle assessments to assess changes in the wood panel industries over time. The evaluation was based on a comparison of life cycle inventory (LCI) data prepared at different times and discussions with experts from the industries.

The LCI data sets considered included the softwood plywood and the oriented strand board (OSB) industries in the U.S. Discussions with mill personal and experts from the industries revealed that several factors such as changes in the economic or market environment, law or regulation changes, developments or new manufacturing technologies contributed to changes in the industries over time that are reflected in changes in the LCI data. However, the primary data collection process itself can result in LCI differences based on different mill respondents.

This study shows that differences in data from successive LCI studies may indicate changes in the industry. However, these apparent changes must be verified through discussion with industry experts.

Introduction

The approach in this study was to attempt to analyze changes in the softwood plywood and oriented strand board (OSB) industries in the U.S. over time. The bases for these comparisons are life cycle inventory (LCI) data sets and qualitative evidence discussed with professionals from the industries.

Miel et al. (2007) assessed wood product processing technology advancements using LCI data from CORRIM I (1970) and the update of the CORRIM II (1999/2000) study. They found a 7% higher recovery efficiency in the plywood industry in 2000 compared to 1970. They stated that this improvement "… is surprising given the decrease in the size and quality of logs; for example, in the PNW peeler log, diameter has decreased by at least 4 inches". Possible explanations included the usage of better lathe technology, which allows to reduce the peeler core, the use of power drive rolls, which in combination with the sounder wood structure origin from the smaller diameter with less core rot reduces 'lathe spinout' and increases efficiency. However, there is the potential for erroneous analysis using this approach, for example, if the apparent differences amongst average values are small compared with the variability in the data, or if the data collected in any one survey period are non-representative in some respect.

An environmental product declaration (EPD) is a standardized summary of LCA data, which describes the environmental burdens associated with the production of a functional unit. The functional unit is a commonly used unit of the considered product or service, for example, one thousand square feet, 3/8 inch thick (MSF 3/8 inch) in the case of softwood plywood and OSB. This functional unit allows a fair comparison of the environmental impacts of these and possible alternative products. The environmental burdens are expressed in commonly used impact categories such as global warming potential (GWP). The methods, units and assumptions for the preparation of the EPD are defined in the Product Category Rules (PCR). The category rules for softwood plywood and OSB is the PCR for North American Structural and Architectural Wood Products (FPInnovations, 2011). This guideline requires an update of the LCI data in a cycle of ten years to ensure representativeness of the values. LCIs were conducted for the production years 1999 for OSB and 2000 for softwood plywood. Therefore, updated LCAs are now required to ensure conformity with the PCR and these updates are underway. Updates of previous studies may also allow analysis of changes in the industries between the studies. The objective of this paper is to investigate if changes in successive LCI datasets can provide useful perspectives on changes in the OSB and plywood industries. For softwood plywood the LCI data for the production year 2000 and 2012 were compared. For the OSB industry, the LCI data of the production years 1999 and 2012 were considered.

Data from Successive Life Cycle Inventories

All data sets were compiled following the ‘Guidelines for Performing Life Cycle Inventories on Wood Products’ (Puettmann et al., 2014). The LCI reports are collections of input and output data within the manufacturing stages. Data from CORRIM I (NRC, 1976), CORRIM II (J. B. Wilson et al., 2004) (Kline, 2004) and the most recent update are summarized in Tables 46 and 47. To ensure consistency with the previous reported data the contribution of softwood plywood producers of the PNW (53%) and SE (47%) regions for the production year 2012 were equally weighted.

Table 46. Comparison of industry average values of softwood plywood production

Input Materials per MSF 3/8 inch Basis	Unit	Softwood Plywood		
		1970	2000[1]	2012[1]
Roundwood	lb	2079.57	1943.52	1863.23
Phenol-formaldehyde resin	lb	20.60	17.91	24.23
Electricity	kWh		130.00	135.35

[1]Equal production level for the PNW and SE region assumed to maintain comparability with reported values from 1970.

Table 47. Comparison of industry average values of OSB production

Input Materials per MSF 3/8 inch Basis	Unit	Oriented strand board 1970	1999	2012
Roundwood	lb	1588.38	1566.00	1568.66
Phenol-formaldehyde resin	lb	60.00	54.40	23.59
Methylene diphenyl diisocyanate resin	lb		8.16	11.60
Wax	lb	12.00	19.30	7.34
Electricity	kWh		182.00	134.12

Tables 47 and 48 indicate differences in average input values for both products, for example, the amount of phenol formaldehyde (PF) resin has apparently increased in plywood production, but decreased in OSB production, between the previous and current updates. However, whether these apparent differences reflect real changes in the industry is uncertain. To help resolve this uncertainty going forward, descriptive statistic such as the weighted coefficient of variation (CV_w) and the documentation of 'Mills reporting a value (n)' were included in the most recent update and will be calculated in the future. This should provide the basis for statistical evaluation of updates in the future to answer questions about whether apparent differences reflect real changes in the industry.

Comparison of Life Cycle Inventory Results of 1999/00-2012

The large amount of variation within the data reported for 2012 shows that small differences in average values between successive LCI studies may not reflect real trends in the industry but rather differences due to sampling uncertainty. For example, Figure 7 shows the variability in 2012 data (as represented by box plots) for three important inputs compared with the average values reported for the year 2000, which is symbolized with the 100% line.

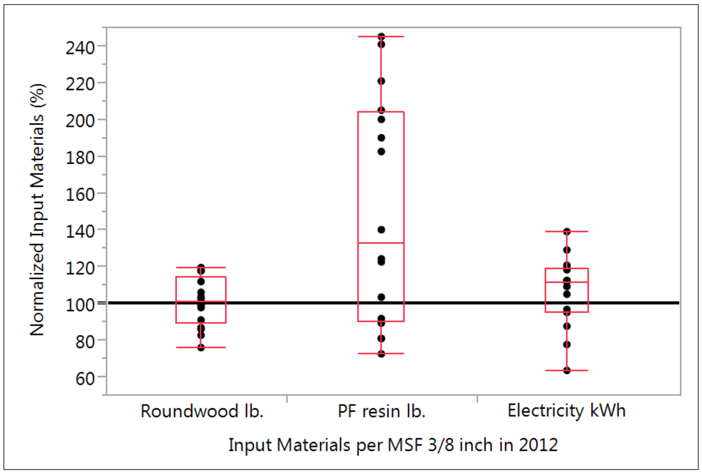

Figure 7. Normalized input materials in % for softwood plywood LCI for 2012

The data set for the production year 2012 with its variation straddles in all three considered groups the documented production-weighted values of 2000. This suggests little evidence for changes in the softwood plywood industry in these three inputs over time.

The following box plot demonstrates the distribution of the LCI's data of OSB for the production year 2012 normalized to the documented values for the production year 1999 (Figure 8).

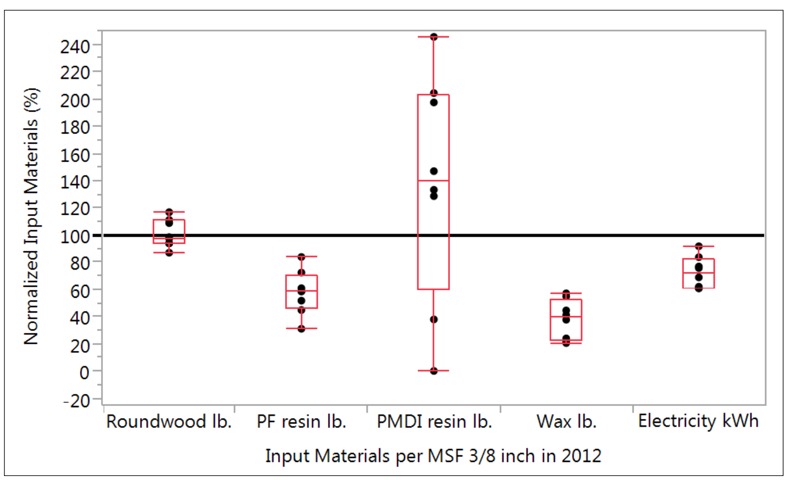

Figure 8. Normalized input materials in % for OSB LCI for 2012

The comparison of the LCI data for 1999 and 2012 shows that roundwood and PMDI resin input straddles the average production-weighted values of 1999. The other input materials such as PF resin, wax and electricity usage per functional unit are lower compared to the production-weighted input in 1999. The lower wax usage could be a result of increased production of "industrial" also called "furniture" grade.

The lower value for PF resin and the big variation of PMDI usage require a more in depth analysis of these components. Therefore, the total resin usage (PF and PMDI combined) were compared with the production-weighted average from 1999 (Figure 9). This approach is justified by the fact that the two different resin systems are commonly combined in the production of OSB boards.

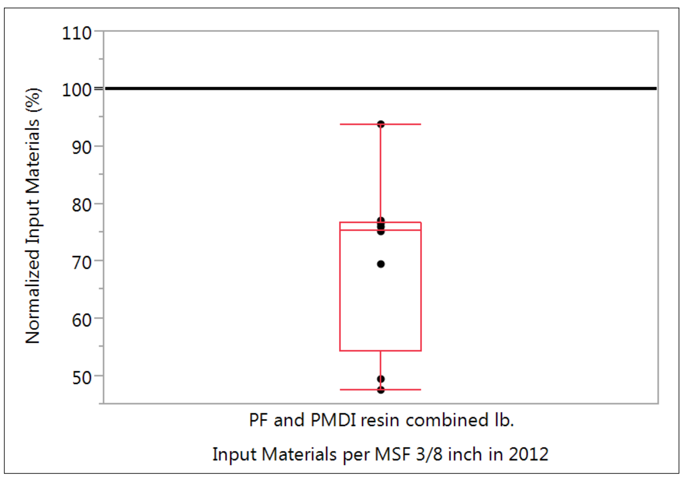

Figure 9. Normalized total resin usage for OSB production for 2012

The reported total resin usage per functional unit in 2012 is lower compared to the production-weighted input in 1999. The lack of statistical descriptions of the previous LCI data sets make a statistical comparison of the successive data sets impossible; however, in the future when uncertainty measurements are provided with the average values, standard statistical test can be employed.

Successive LCI reports have shown differences in average values and high variation amongst the reporting mills. Therefore, the apparent trends in the LCI data over time should be considered within the context of other factors that are affecting the industry.

Potential Factors for Changes in Life Cycle Inventory Results

Developments such as the harsh economic environment caused by the economic crises in 2006 and its aftermaths, efforts to enter new market segments, the lowering of maximum allowed emissions caused from the production process and further development of resin technology could be contributors for changes in the wood-based panel industries reflected in the LCI results.

Production versus Capacity

The utilization of the available production capacity is an important key figure for comparisons and can also have an impact on the LCA results. Softwood plywood and OSB producers are directly linked to the commercial and residential building industries because 52% and 72% of softwood plywood and OSB produced in the U.S. is used in construction (APA, 2013a). Therefore, the economic crises and its impact on the building sector resulted into a drastic change within the wood structural panel industries in the U.S. The plywood industry used 94% of the available production capacity in 2000 but only 76% in 2012. In addition the available production capacity of softwood plywood in the U.S. reduced by 35% over those twelve years. The OSB industry used 95% of the available production capacity in 1999 and 68% in 2012. Although the total OSB production capacity has increased by 33%, there was a decreased actual production output by 5% within the thirteen years (APA, 2013a).

Puettmann et al. (2012a) stated that based on "the collapse of the U.S. housing market, a lot of smaller inefficient mills were closed during 2006-2010". This trend may be refelected in the output per employee. The documented weighted average output of softwood plywood in the production years 2000 and 2012 was 658 and 812 MSF 3/8 inch basis per employee.

Effects of the utilization rate on the representative LCI values can be caused by non-linear processes in the production chain. Although input materials may have a linear increase of amount proportional to the prodution output, the per unit energy input may be disproportional affected when the same machinery is used at higher or lower production rates.

According to the survey results, eleven of seventeen softwood plywood mills and four of eight OSB mills are tracking electricity usage within the individual production steps. These details allow a ‘sub-unit’ model instead of a ‘black box’ calculation model. The ‘sub-unit model’ could help to reveal trends based on the individual production steps, which are potentially covered by the data variability of the total input values. A possible example is the reduction of press temperature by alternative gluing systems, which results into savings of energy sources such as hogged fuel and natural gas. If this reduction is associated with changes in emission regulations, which requires an increase of natural gas usage in the emission control devices, this trend would not have been visible in the ‘black box model’ and in the overall LCI results.

Efforts to Enter New Market Segments

In the 2012 LCI update, a lower wax usage per functional unit was reported (Figure 8). This could be because, as the demand for wood-based building panels for the sheathing applications was down in the building sector, many of the mills tried to shift towards the production of “industrial” or “furniture grade”. These grades describe the application of OSB panels for upholstered furniture frames, core stock for industrial grade tables and other applications “… without specific appearance or surface properties” (SBA, 2007). Although the total panel use in furniture production and manufacturers in the U.S. decreased about 30% between 2005 and 2012, OSB use overall increased significantly. In 2005 about 0.4% of the U.S. furniture manufacturers reported the usage of OSB. Seven years later 34% of the producers reported the usage of OSB (APA, 2013b). This shift, particularly in the OSB industry, allowed some modifications in the production process because of the different applications without the need to resist severe conditions. This shift provided a cost reduction potential because of a reduction of the wax content.

Changes in Emission Regulations

Changes in emission regulations by the United States Environmental Protection Agency (EPA) towards lower maximum emission values for 'Industrial/Commercial/Institutional Boilers and Process Heaters' had a direct effect on the wood industries. Within the years of the compared CORRIM studies, several updates were discussed and finalized (EPA, 2014), which required the implementation of emission control devices (ECDs) by wood processing companies. To describe the changes of the regulations in detail is beyond the scope of this paper, but according to the survey information twelve of seventeen plywood mills and four of eight OSB mills documented the installation of at least one ECD in the years between 1999 and 2012.

The employment of ECDs requires a significant amount of gas or electricity to reduce hazardous air pollutants (HAPs), volatile organic compounds (VOCs) and PM produced in the thermal energy production and the wood drying process.

The introduction of ECDs to fulfill tightened emission regulations should therefore be mirrored in higher consumption of these energy sources in LCIs. A comparison of these energy sources in the context of the recent LCIs results is shown in Table 48.

Table 48. Comparison potential energy sources emission control devices

Potential Energy Sources ECDs	Unit	OSB Quantity per m^3		PNW Plywood Quantity per m^3		SE Plywood Quantity per m^3	
		1999	2012	2000	2012	2000	2012
Electricity	kWh	2.06E+02	1.52E+02	1.57E+02	1.45E+02	1.38E+02	1.58E+02
Natural gas	m^3	2.39E+01	2.15E+01	5.22E+00	1.27E+00	7.74E+00	2.80E+01
Liquid petroleum gas	l	3.03E+00	2.83E-01	1.54E+00	2.13E+00	1.80E+00	2.14E+00

The results of this comparison show a lower usage of potential energy source for ECDs in the OSB industry. Softwood plywood in the PNW reported also lower values per functional unit except for LPG, which increased 28%, compared to the LCIs data from 2000. The softwood plywood producers in the SE reported higher values in the three potential energy sources compared to the LCIs data from 2000. Besides the potential influence factor of extensive production of ‘sold veneer’ (139 kg per m^3 softwood plywood) in the SE the variability within the data and different mill responses can contribute to these apparent differences.

Developments in Resin Technology

Improved blending technology should allow a lower resin input per functional unit according to experts from the OSB industry. The mills’ specific resin formulation and the associated large variation within the data sets was discussed in the comparison of the LCI results from 1999 and 2012 (Figure 9). According to the literature, MDI has a faster curing process, which allows an increase of production speed resulting into higher production output (FPL, 2010). Experts of the OSB industry emphasized that this trend is real because MDI is more robust to typical process variation such as moisture content in wood, tolerates higher moisture content in the wood during the manufacturing process than PF resin systems, allows higher physical performance based on the combination of mechanical and chemical bond, and ensures a higher moisture resistance of the final product (WBPI, 2012).

The on-going discussion regarding formaldehyde emissions caused by PF resin systems in wood composites is likely a minor reason for softwood plywood and OSB producers to shift towards MDI. Structural wood panels are meeting, or are exempt from, the leading formaldehyde emission standards such as regulations of the U.S. Department of Housing and Urban Development (HUD), California Air Resources Board (CARB) and the Japanese Agricultural Standards (JAS) (APA, 2014).

Despite further developments of MDI resin systems, including release agents, none of the eight OSB mills reported the usage of MDI exclusively. The mills reported different ratios between the resin systems in the outer and middle layer; seven reported the usage of MDI only in the middle layer; one mill reported the usage of PF binders only. Mill personnel stated that this combination of two resin systems should avoid problems with sticking of MDI on contact surfaces in the production process.

Despite the mentioned advantages of MDI, it is more costly (FPL, 2010) and has a different environmental performance than PF resin systems. A comparison in form of a sensitivity analysis, which assumed the exclusive usage of MDI by replacing the PF share with 30% less MDI should provide a functional equivalence of the final product and illustrates potential environmental impacts of the shift towards isocyanate based resin systems. The stated percentage was based on information from experts that stated a possible reduction of 24 to 42% of MDI resin input by ensuring the same mechanical properties of the final product. Table 49 shows the comparison of "case1", which describes the reported resin mix 2012 and "case 2", which describes the exclusive MDI resin usage.

Table 49. Sensitivity results of environmental impacts of case1 and case2

Impact category	Unit	Case 1 m^3	Case 2 m^3	Change[1] %
Global warming potential (GWP)	kg CO_2 equiv	2.50E+01	3.35E+01	34
Acidification potential	H+ moles equiv	2.24E-01	1.39E-01	-38
Eutrophication potential	kg N equiv	1.63E-02	4.21E-03	-74
Ozone depletion potential	kg CFC-11 equiv	6.78E-07	1.43E-06	110
Smog potential	kg O3 equiv	1.37E+00	1.43E+00	4

[1]Potential impact increase demonstrated by positive percentages.

The comparison shows an increase of the potential environmental impact in three of the five required potential environmental impacts according to the PCR.

The efforts of wood-based panel producers in the U.S. to be competitive on the global market demands continuous optimizations of the inputs and the production process to reduce costs. This trend, which is economically driven, can also have an impact on the environmental performance of the final product. Hence, one can state that there is a direct linkage between the economic and ecological nature of the final product because a lower input of resources results in general to a lower environmental impact.

Conclusion

The analysis of this study emphasizes the need for the holistic consideration of processes to evaluate changes in industries over time. It is difficult to identify and analyze changes over time exclusively based on the LCI results or the calculated environmental impact because several factors can influence these data.

Differences can result from changes in the economic or market environment, law or regulation changes, developments or new manufacturing technologies and survey responses. These differences may be reflected in changes in average reported values for inputs such as roundwood, resin, wax and energy sources.

The use of a functional unit allows the comparison of competing products although it can result into a loss of information by ‘normalizing’ individual products into this unit. Attributes such as grades and density differences based on specific thicknesses of the final product can get lost. Another example is the ‘furniture or industry’ quality in OSB, which does not require wax input versus the usage in the traditional applications of the board. Trends that affect the key figures may not be traceable by comparing only the functional units without considering other potential factors.

Statistical comparison methods can provide evidence that the data sets are different beyond the variation of the individual data sets. However, these tools require a statistical description of the data sets, which are not available for the data sets of the previous studies. The need for documenting the estimates of error is underlined by incorporating these into the updated ‘CORRIM Guidelines for Performing Life Cycle Inventories on Wood Products 2014’.

Even when estimates of error are available, the potential bias of different responding companies can have an effect on the evaluation. Therefore, a combination of the “hard facts” resulting from statistical methods and the expertise of professionals of the industries should be used because the absence of statistical proof of changes in key figures does not imply that the industries did not develop or change at all.

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Acronyms

APA	The Engineered Wood Association
BF	Board foot
CIBO	Council of Industrial Boiler Owners
CORRIM	Consortium for Research on Renewable Industrial Materials
CV	Coefficient of variation
ECD	Emission control device
EPA	United States Environmental Protection Agency
EPD	Environmental Product Declaration
ESP	Electrostatic precipitator
GWP	Global warming potential
HAP	Hazardous air pollutants
ISO	International Organization for Standardization
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
LPG	Liquefied petroleum gas
MC	Moisture content
MCAT	Maximum Achievable Control Technology
MDI	Methylene diphenyl diisocyanate
MSF	Thousand square feet
NREL	National Renewable Energy Laboratory
OSB	Oriented strand board
PCR	Product Category Rule
PF	Phenol formaldehyde
PM	Particulate matter
PNW	Pacific North West USA
RNA	Country Code North America
RCO	Regenerative catalytic oxidizer
RTO	Regenerative thermal oxidizers

SE	South East USA
SBA	Structural Board Association
TRACI	Tool for the Reduction and Assessment of Chemical and other Environmental Impacts
VOC	Volatile organic compound
VRR	Veneer recovery ratio
WESP	Wet electrostatic precipitator

Conversion Factors

Conversion from	to	multiply by
Linear Units		
inch (in)	Centimeter (cm)	2.54
Centimeter (cm)	inch (in)	0.39
3/8 inch	Centimeter (cm)	0.95
Foot (ft.)	Meter (m)	0.3
Meter (m)	Foot (ft.)	3.28
Mile	Kilometer (km)	1.61
Kilometer (km)	Mile	0.62
Square Units		
Square foot (ft^2)	Square meter (m^2)	0.09
Square meter (m^2)	Square foot (ft^2)	10.76
Volume Units		
MSF 3/8- inch basis	Cubic meter (m^3)	0.89
Cubic meter (m^3)	MSF 3/8- inch basis	1.13
Cubic foot (ft^3)	Cubic meter (m^3)	0.03
Cubic meter (m^3)	Cubic foot (ft^3)	35.32
Board foot (BF)	Cubic foot (ft^3)	0.08
Cubic foot (ft^3)	Board foot (BF)	12
Board foot (BF)	Cubic meter (m^3)	0.0023597
Cubic meter (m^3)	Board foot (BF)	423.78
Fluid Units		
Gallons U.S. (Gal)	Liter (l)	3.79
Liter (l)	Gallons U.S. (Gal)	0.26

Weight Units

Kilogram (kg)	Pound (lb.)	2.2
Pound (lb.)	Kilogram (kg)	0.45

Energy Units

British thermal unit (BTU)	Mega joule (MJ)	0.0010551
Mega joule (MJ)	British thermal unit (BTU)	947.82
Kilowatt - hour (kWh)	Mega joule (MJ)	3.6
Mega joules (MJ)	Kilowatt - hour (kWh)	0.28

Wood Units

metric ton (t)	short ton (ton)	1.1
short ton (ton)	metric ton (t)	0.907184
green ton	Pound (lb.)	2000

VITA

Dominik Kaestner was born on July 11, 1984, in Salzburg, Austria. He graduated with an undergraduate degree in Forest Product Technology and Timber construction with the concentration on Wood Technology in 2012 from the University of Applied Sciences Salzburg, Austria. Dominik joined a masters' dual degree program possible by the collaboration between The University of Tennessee in Knoxville, USA and the University of Applied Sciences in Salzburg, Austria. He was selected as a Marshall Plan Scholar.