GATE-TO-GATE LIFE-CYCLE INVENTORY OF I-JOIST PRODUCTION

James B. Wilson
Professor

and

Eric R. Dancer
Former Graduate Research Assistant
Department of Wood Science and Engineering
Oregon State University
Corvallis, OR 97331

ABSTRACT

A life-cycle inventory (LCI) study is conducted of wood composite I-joists manufacturing. This gate-to-gate study includes all materials, fuels, and electricity inputs to produce I-joists, co-products, and emissions. The inputs included the laminated veneer lumber (LVL) used for the I-joist's flanges and the oriented strandboard (OSB) used for the web, but it excluded the LCI for their input logs. Data were collected through surveys of manufacturing facilities in the Pacific Northwest and the Southeast. In addition to LCI data, transportation distances for delivery of materials are also provided. SimaPro software, a program to conduct life-cycle inventory and assessment studies, is used to process the data and determine environmental impacts in terms of material and energy use, and emissions. The impact data are allocated on a mass basis to I-joist based on their mass contribution to the sum of all product and co-product generated during the manufacturing process. All data are provided on a production unit basis of 1.0 km and 1.0 MLF (one thousand linear feet), the U.S. industry practice. In addition to LCI data, carbon flow data are also given. These LCI data are publicly available through comprehensive reports, this summary publication, and the U.S. Life-Cycle Inventory Database Project. The data are useful for generating cradle-to-gate product LCIs when combined with the LCIs to produce logs for the mills and material transportation impacts, and are useful as a benchmark for assessing process performance, and for conducting life-cycle analysis of floor and roof assemblies and residential structures using I-joists.

Keywords: Life-cycle inventory, LCI, I-joists, building materials, carbon balance, energy, emissions.

INTRODUCTION

Background

Composite wood I-joists, or simply referred to as I-joists, are relatively new wood-based building materials that are designed to replace structural lumber in floor and roof joist systems and to be competitive with steel floor and roof systems. Composite I-joists are engineered products and are comprised of two different main components. As the name implies, these products have an "I" shaped cross-section with the top and bottom flanges separated by a narrow "webbing" material, (see Fig. 1). In most modern I-joists, the flanges are made from laminated veneer lumber (LVL) that has been ripped into specific dimensions, while the web material is generally made from oriented strandboard (OSB). In some instances, the flange material is made from solid-sawn lumber and the web material can be made from plywood. There are many different dimensions of composite I-joists but the most common are dimensions that directly replace 2 × 10-inch and 2 × 12-inch structural lumber. I-joists are usually made in continuous lengths and then cut to 60-foot lengths for shipping. This study focused on large-scale production facilities that would be representative of the industry.

This study documents the life-cycle inventory

Wood and Fiber Science, 37 Corrim Special Issue, 2005, pp. 85 – 98

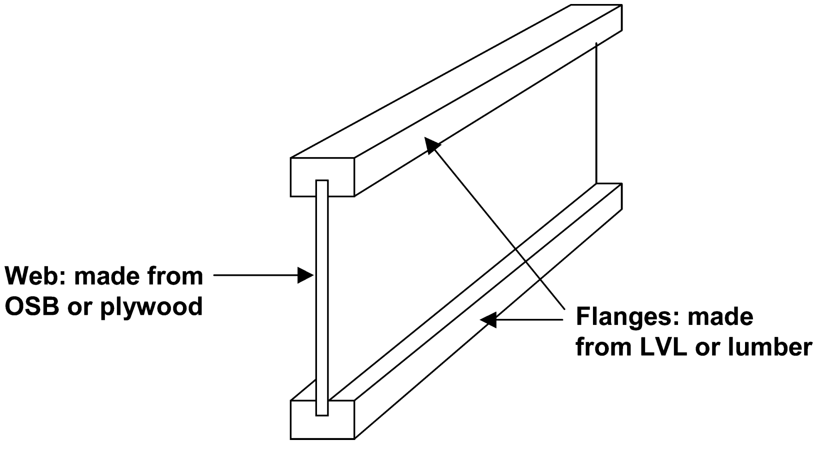

FIG. 1. Diagram of the cross-section of a typical composite I-joist.

(LCI) of manufacturing I-joists based on current manufacturing practices in the Pacific Northwest and the Southeast of the U.S. All of the inputs used to make I-joists are generated in the region where they are produced with the exception of OSB. There are no facilities in the PNW that produce OSB; therefore it is usually shipped from either the upper mid-western U.S. or northwestern Canada. The industry measures their production of I-joist in linear feet since a volume measure is unrealistic because of their I-shape. In 2000, the total I-joist production in the PNW was 212,000 thousand linear feet (MLF) and in the SE it was 284,000 MLF (APA 2001). This study is part of the Consortium for Research on Renewable Industrial Materials (CORRIM) Phase I project to study the life-cycle assessment (LCA) of renewable building materials (Bowyer et al. 2004; Lippke et al. 2004; Perez-Garcia et al. 2005). The I-joist LCI data can be used by practitioners of LCI and LCA to assess the product and its use in buildings in any overall cradle-to-grave analysis. These data are also available in the U.S. Life-Cycle Inventory (LCI) Database Project, along with a large number of other materials and processes (NREL 2005).

Scope of study

The scope of this study was to develop a life-cycle inventory (LCI) and carbon flow for the production of I-joists based on current manufacturing practices in the Pacific Northwest (Oregon and Washington) and the Southeast (Alabama, Arkansas, Florida, Georgia, Louisiana, Mississippi, and Texas). This study analyzes the gate-to-gate LCI of I-joists that includes the environmental impacts of the LVL and OSB as input to the I-joist plant, as well as all impacts associated with its manufacture. It covers the impacts in terms of input materials, fuels, and electricity through the outputs of product, co-product, and emissions. The study excludes the impacts for growing and harvesting of logs, and the transportation of materials to the LVL, OSB, and I-joist production facilities. Transportation data are provided in terms of mileage of products delivered to the plants. For a cradle-to-gate LCI, the LCI data for I-joists would need to be combined with the LCI data for the logs and transportation of materials. The primary data collection was done with surveys of I-joist manufacturers, while secondary supporting data were also used. The LCI models and data for LVL and OSB were from other CORRIM projects developed by Wilson and Dancer (2004a) and Kline (2004), respectively. The secondary data were necessary to assess the impacts of using these materials in the I-joist process. Electricity and fuel data were gathered from Franklin Associates (FAL 2001), PRe' Consultants (2001), and the U.S. Department of Energy

(USDOE 2001), while information related to the production of phenol-formaldehyde resin (a substitute for phenol-resorcinol-formaldehyde resin data) came from ATHENA™ (1993), and the isocyanate from Pre' Consultants (2001). All the plants surveyed also produced LVL at the same facility; however, only data related to I-joist manufacturing were recorded for this study, relying on the LCI models for LVL for their impact analysis.

For the two major components of I-joists, LVL is manufactured in the PNW primarily from Douglas-fir (*Pseudotsuga menziesii* (Mirbel) Franco) veneers, while the OSB must be shipped from other regions in the U.S. or from Canada. In the SE, LVL and OSB are also the most common inputs to manufacture I-joists. The LVL is made from a combination of pine species, primarily loblolly (*P. taeda* L.) and slash (*P. elliottii* Engelm.), which are known as southern pine. I-joist plants were surveyed in each region to record all input and output data associated with the manufacturing process for the production year 2000. In the PNW the surveyed mills represented almost 33% of the total production of I-joists for the region and in the SE represented approximately 27% of the total production in that region. The quality of the data collected is considered good for this type of study based on between-plant comparisons and mass and energy balances.

Production of I-joists is measured in lineal feet with no measurement for the dimensions of height and width, which is the practice for the I-joist data given in this study. The most common dimensions of I-joist for the PNW are 9.5 × 1.3125 × 1.75 inches., 11.875 × 1.3125 × 1.75 inches, and 11.875 × 3.125 × 1.5 inches (dimension of I-joist height, flange thickness and width); whereas for the SE the most common dimensions are 9.5 × 1.5 × 1.75 inches, 11.875 × 1.5 × 1.75 inches and 11.875 × 1.5 × 1.5 inches. For LCI data for each of these I-joists, see Wilson and Dancer (2004b). A weighted average of inputs was calculated for producing a generic I-joist in each geographical region studied. The input units of LVL and OSB are given on a volume basis and are used as inputs into I-joist production on this basis. The unit of output is 1.0 thousand linear meters (km) or 1.0 thousand linear feet (MLF) with no regard to flange thickness and width or I-joist height. Based on the data obtained from the surveys, the generic I-joist in the Pacific Northwest has a depth of 11.75 inches and a flange of roughly 1.3125 inches thick and 1.875 inches wide. This I-joist is slightly larger than you would expect to find in that region. In the Southeast, the survey data also result in an I-joist with larger dimensions than one would expect to find in a typical I-joist. The reason for the generic I-joists being larger than typical I-joists is due to the small amount of waste and inefficiencies of producing the I-joists included in the product.

To conduct the survey, plants were identified in each region based on their production capabilities and their representativeness of the industry. Each mill provided data based on I-joists and co-product production, raw material usage, electricity and fuel usage, emissions, and transportation data for input materials.

External critical reviews were made of this LCI study of I-joist to assure that the methodology, data collection, and analyses are scientifically sound, and are in compliance with CORRIM protocol and ISO 14040 and 14041 standards (CORRIM 2001; IS0 1997; ISO 1998). Complete details of this study for I-joist production and the overall CORRIM project can be found in Wilson and Dancer (2004b) and Bowyer et al. (2004), respectively.

I-joist process and description

Two life-cycle inventory models were created for I-joist manufacturing, one for the PNW region and another for the SE region. A black-box approach was taken, which simply means that all process inputs and outputs are lumped together into one I-joist process (Fig. 2). The black-box approach is used because of the relative simplicity of the I-joist manufacturing process having such a small number of unit processes and because a high percentage (about 90%) of environmental burdens are allocated to I-joists. The input materials of laminated veneer lumber (LVL)

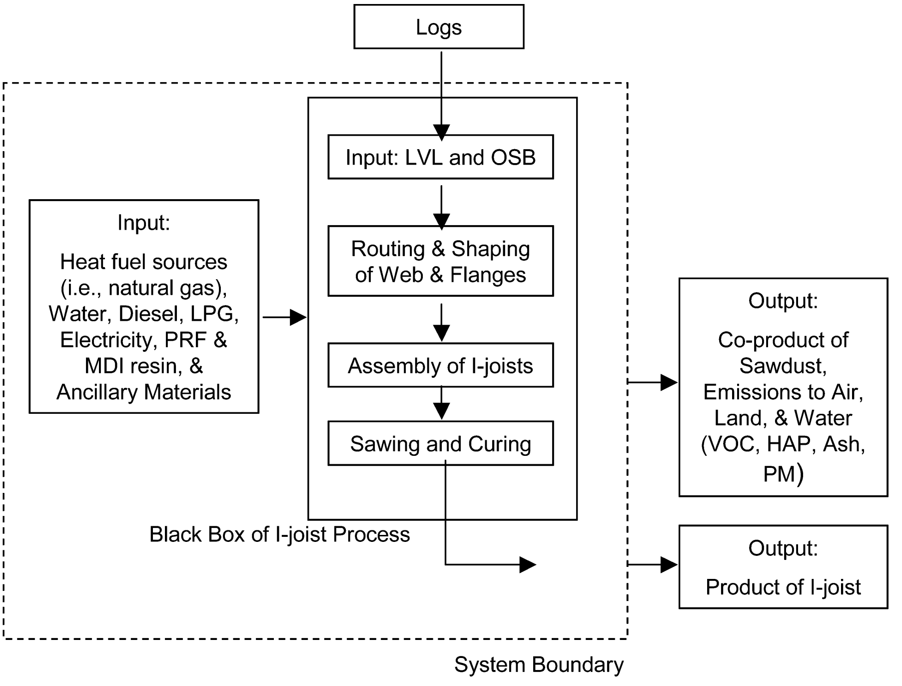

FIG. 2. Breakdown of unit processes in composite I-joist manufacturing.

and oriented strandboard (OSB) are included as part of the process even though these materials are produced in separate operations either at the I-joist plant or other plants; they are both considered within the system boundary.

The following is the description of process steps within the "Black Box" for producing I-joist:

1. Routing/Shaping of web and flanges: Includes the machining of the OSB web pieces to be fit together at the ends as well as tapered on the top and bottom edges so that they can be fitted into the LVL flanges. The LVL flanges are routed their entire length to accept the inserted tapered OSB web material. The co-product created during this process is sawdust.
2. Assembly of I-joist: Web and flange material are assembled after resin (usually phenol-resorcinol-formaldehyde or isocyanate) is applied in web-to-web and web-to-flange joints. Assembly is done mechanically, pressing web sections end-to-end and into the top and bottom flange which are also pressed end-to-end; the result is a continuous ribbon of I-beam that can be of infinite length. No co-products are created.
3. Sawing/Curing: Continuous ribbons of I-joists are cut to proper lengths and in some cases heated in an oven to accelerate resin cure of the joints.

Functional unit

The functional unit for I-joist is 1.0 thousand linear meters (km) or 1.0 thousand linear feet (MLF). For conversion from the U.S. industry measure, 1.0 MLF is equal to 0.3048 km. All input and output data were allocated to the functional unit of product based on the mass of products and co-products in accordance with CORRIM and ISO protocol (CORRIM 2001; ISO 1997, ISO 1998).

System boundaries

The life-cycle inventory (LCI) data were done considering the cumulative materials and energy use, and emissions, considering both site and off-site related impacts to produce I-joists, OSB, LVL, electricity, fuels, and resins (Fig. 2). For this cumulative system boundary, only the impacts of growing and harvesting logs and the impacts of transporting materials to the I-joist plant are excluded.

Assumptions

The protocol for this LCI study can be found in "Consortium for Research on Renewable Industrial Materials (CORRIM)—Research Guidelines for Life Cycle Inventories" dated April 10, 2001 (CORRIM 2001). Other considerations include:

1. Data quality was found to be high based upon comparisons between plants, and on mass and heat balances. Data were also compared between geographical regions and were found to be consistent when accounting for the higher density and moisture contents of wood species of the Southeast.
2. The data were collected from the mill survey for the 2000 production year, and were weighted based on the production levels of the participating plants.
3. A mass-allocation process based on the contribution of the product and co-product was used for assigning burdens such as emissions.
4. Co-products were defined as those materials that were sold outside the system boundary.
5. Laminated veneer lumber inputs were given on a volume basis of cubic feet (ft^3) and OSB inputs were given on a volume basis of MSF 3/8's (1,000 square feet of surface by 3/8-inch-thick equivalence) and converted to mass based on the values found in Wilson and Dancer (2004a) and Kline (2004).
6. SimaPro life-cycle inventory (LCI) models for LVL were imported from those developed by Wilson and Dancer (2004a), and for OSB using a black-box model developed from data found in Kline (2004).
7. All conversions for forest products are taken from Forest Products Measurements and Conversion Factors, with special emphasis on the U.S. Pacific Northwest (Briggs 1994).

SimaPro version 5.0.009, a software package designed to analyze products through their entire life cycle, was used to complete the LCI. Developed in the Netherlands, the software is designed by PRe' Consultants and contains a database for U.S. materials which includes, but is not limited to, paper products, fuels, and chemicals (PRe' Consultants 2001). The U.S. database is provided by Franklin Associates (FAL 2001).

Material flows

Delivery of the input materials was by both truck and train. Large distances were involved with transportation of OSB to the PNW region since there are no plants in this region that produce it. The values for LVL shipping distances are zero since the surveyed I-joist plants also produce LVL on-site. The one-way delivery distances for the PNW and the SE are shown in Table 1. The delivery distance and the amount of materials shipped would be used in any cradle-to-gate LCI analysis for I-joists, in addition to the transportation distances given for the production of OSB and LVL that are given in Kline (2004) and Wilson and Dancer (2004b), respectively.

A product mass balance in and out of the I-joist manufacturing for each region was completed and is given in Table 2. The LVL and OSB, and the I-joist and sawdust outputs all include resin since they were common to all products. The balance of inputs and outputs were

TABLE 1. *Delivery distances (one-way) for inputs to I-joist manufacturing facilities.*

	Pacific Northwest delivery distance		Southeast delivery distance	
Material delivered	km	mile	km	mile
OSB	3026	1880	515	320
LVL	0	0	0	0
I-joist (PRF/MDI) resin	n/a	n/a	1191	740
Web-to-web joist (MDI) resin	470	292	n/a	n/a
Web-to-flange (MDI) resin	237	147	n/a	n/a

within 0.5% of each other. The allocation of environmental burdens for the LCI analysis is done on a mass basis (Table 2), with 89.8% and 93.0% assigned to the I-joist produced in the PNW and SE, respectively. The remaining percentage of the burdens is assigned to the sawdust co-product.

Input to produce 1.0 km or 1.0 MLF of composite I-joists varied between the two regions, (see Table 3). These data were input to the SimaPro software to develop the LCI model. The data for the input come from surveys and have no dimensions other than a linear measure of output. This output should be considered generic for the output of 1.0 MLF of I-joists in each region. I-joists that differ in size will have different input volumes and require further analysis. The LCI data for the three most common I-joist dimensions, which are replacements for structural lumber 2 × 10s and 2 × 12s, for each production region are given in Wilson and Dancer (2004b). The product weights differ between regions as a result of the density differences of the LVL and the dimension differences. Whereas different LVL was used for each region, the OSB was treated as having the same characteristics for both regions with only the shipping distance differing. To produce 1.0 km of I-joist in the PNW, it took 1,680 kg of LVL, 1,640 kg of OSB, and only 18.2 kg of an isocyanate (MDI) type resin, whereas for the SE it took 2,400 kg of LVL, 1,770 kg of OSB, and 7.74 kg of MDI and 4.54 kg of phenol-resorcinol-formaldehyde (PRF) resins. The major use of energy for manufacturing was the use of electricity and natural gas, with minor amounts of liquid petroleum gas (LPG) and diesel to operate forklifts and haulers. The product input weights were based on values for the density of the input products and the amount of those inputs into the manufacturing process. The value for LVL was determined in each region based on the veneer input species density given in the Wood Handbook (FPL 1999) and a 10% increase in weight after resin was added and the product was pressed, which would increase the density. The OSB density that was used in this report was obtained from Kline (2004). Other inputs to the SimaPro model included the site emissions from the NCASI (1999) reports for the production of I-joists, (see Table 4). The Franklin database in SimaPro provides the emissions for diesel, LPG, and natural gas, as well as the emissions for the production of electricity based on the fuel source mix for generation.

The data in Tables 3 and 4, and the SimaPro LCI models for LVL (Wilson and Dancer 2004a) and OSB (Kline 2004) were input into the LCI model developed in SimaPro for the PNW and SE production regions. Figure 2 provides the cumulative system boundary used to determine what impacts are considered. The life-cycle inventory output of this analysis gives the product and co-product produced, as well as the raw materials, electricity and water usage, see Table 5. The inputs consider the raw materials

TABLE 2. *Product mass balance for manufacturing a unit of I-joist. All weights[1] are reported on an oven-dry basis, and production units are on linear dimension of km or MLF (thousand linear feet).*

	PNW			SE		
Inputs	kg/km	lb/MLF	Allocation[2] %	kg/km	lb/MLF	Allocation %
Laminated veneer						
Lumber	1.68E + 03	1.13E + 03		2.40E + 03	1.61E + 03	
Oriented strandboard	1.64E + 03	1.10E + 03		1.77E + 03	1.19E + 03	
Resins	1.82E + 01	1.22E + 01		1.22E + 01	8.20E + 00	
Total	3.34E + 03	2.24E + 03		4.18E + 03	2.81E + 03	
Outputs	kg/km	lb/MLF		kg/km	lb/MLF	
Composite I-joists	3.01E + 03	2.02E + 03	89.8	3.87E + 03	2.60E + 03	93.0
Sawdust	3.42E + 02	2.30E + 02	10.2	2.92E + 02	1.96E + 02	7.0
Total	3.35E + 03	2.25E + 03	100	4.16E + 03	2.80E + 03	100

[1] The weight of LVL, OSB, I-joist and sawdust includes weight of resin.
[2] The allocation factor for assigning environmental burdens in the life-cycle inventory is done on a mass contribution basis of product and co-product.

TABLE 3. *Gate-to-gate life cycle inventory (LCI) inputs to produce a unit of I-joist[1]. These are unallocated values.*

	PNW I-joist		SE I-joist	
Inputs material[2]	kg/km	lb/MLF	kg/km	lb/MLF
MDI (isocyanate) resin	1.82E + 01	1.22E + 01	7.74E + 00	5.20E + 00
PRF (phenol-resorcinol-formaldehyde)				
Resin	n/a	n/a	4.54E + 00	3.05E + 00
Laminated veneer lumber	1.68E + 03	1.13E + 03	2.40E + 03	1.61E + 03
Oriented strandboard	1.64E + 03	1.10E + 03	1.77 + 03	1.19E + 03
Electrical use	MJ/km	kWh/MLF	MJ/km	kWh/MLF
Electricity	9.94E + 02	8.41E + 01	8.87E + 02	7.51E + 01
Fuel use	L/km	gal/MLF	L/km	gal/MLF
LPG (liquid petroleum gas)	2.04E + 00	1.64E − 01	4.72E + 00	3.80E − 01
Diesel	9.94E − 01	8.00E − 02	3.60E + 00	2.90E − 01
	m^3/km	ft^3/MLF	m^3/km	ft^3/MLF
Natural gas	4.60E − 01	4.95E + 00	5.95E + 00	6.40E + 01
Water usage	kg/km	lb/MLF	kg/km	lb/MLF
Municipal water source	2.11E + 02	1.42E + 02	6.41E + 02	4.31E + 02
Recycled water	0.00E + 00	0.00E + 00	2.86E + 01	1.92E + 01
Well water source	0.00E + 00	0.00E + 00	4.21E + 01	2.83E + 01

[1] Survey data for I-joist plant site collected for 2000.
[2] All materials are given on an oven-dry or solids weight basis.

TABLE 4. *I-joist site emissions[1] input to LCI SimaPro model.*

	PNW I-joist		SE I-joist	
Emissions	kg/km	lb/MLF	kg/km	lb/MLF
Acetone	0.0002	0.00014	0.0002	0.00014
Formaldehyde	0.0003	0.00018	0.0003	0.00018
Methanol	0.0253	0.01700	0.0253	0.01700
Particulate			0.0417	0.02800

[1] Data source: NCASI (1999).

use of LVL and OSB, and the PRF (substituted phenol formaldehyde in analysis because PRF data were not available) and MDI resins, and the primary fuels used to produce and deliver the fuels, electricity, and resins, and the water use for the manufacture of OSB, LVL, and I-joists. The outputs are allocated to 1.0 km of I-joist based on each production region's allocation factor based on mass; it was 89.8% and 93.0% for the PNW and SE, respectively. The outputs exclude the impacts for the logs to produce the LVL and the OSB, and exclude the transportation of materials to the LVL, OSB, and I-joist plants. For a cradle-to-gate analysis from the forest to the output gate of the I-joist plant, these data would need to be combined with the LCI data of harvested logs (Johnson et al. 2004), and the transportation data of materials to the plants (Wilson and Dancer 2004a; Kline 2004) and Table 1.

MANUFACTURING ENERGY

Energy for the production of I-joists in the both PNW and SE comes from electricity, natural gas, diesel, and liquid petroleum gas (LPG). None of the plants that were surveyed used hogged fuel (wood and bark waste fuel) as a source of energy in the manufacturing process. The electricity in the plant is used to run the various saws and assembly machinery in the I-joist plant. The natural gas is used to generate heat in order to cure the resin used in the I-joist assembly. The diesel fuel and LPG are used to operate the equipment that moves the input material and output product around the manufacturing facility.

The source and type of fuel used to generate electricity for the manufacturing of I-joists are vital for a thorough LCI analysis. Each region that was analyzed had its own unique and different sources of electricity generation; the breakdown of electricity generation by fuel source is shown in Table 6. The data are ob-

TABLE 5. *Life-cycle inventory (LCI)[1] outputs to produce I-joist. All weights except water are on an oven-dry or solids basis.*

Product	PNW I-joist		SE I-joist	
	kg/km	lb/MLF	kg/km	lb/MLF
Composite I-joists	3.01E + 03	2.02E + 03	3.87E + 03	2.60E + 03
Co-products	kg/km	lb/MLF	kg/km	lb/MLF
Sawdust	3.42E + 02	2.30E + 02	2.92E + 02	1.96E + 02
Raw materials	kg/km	lb/MLF	kg/km	lb/MLF
Bark on logs (for LVL)	6.83E + 01	4.59E + 01	1.01E + 02	6.80E + 01
Logs (for LVL)	1.36E + 03	9.12E + 02	2.02E + 03	1.36E + 03
Bark on logs (for OSB)	1.48E + 02	9.92E + 01	1.65E + 02	1.11E + 02
Hardwood logs (for OSB)	4.66E + 02	3.13E + 02	5.24E + 02	3.52E + 02
Softwood logs (for OSB)	1.39E + 03	9.35E + 02	1.56E + 03	1.05E + 03
Coal	1.55E + 02	1.04E + 02	3.21E + 02	2.16E + 02
Crude oil	1.06E + 02	7.13E + 01	1.31E + 02	8.78E + 01
Limestone	1.12E + 01	7.50E + 00	2.40E + 01	1.61E + 01
Natural gas	2.24E + 02	1.50E + 02	3.15E + 02	2.12E + 02
Uranium	7.87E − 04	5.29E − 04	1.62E − 03	1.09E − 03
Wood/wood waste[2]	2.67E + 01	1.79E + 01	8.84E + 01	5.94E + 01
Wood fuel (biomass)[3]	9.50E + 02	6.38E + 02	1.16E + 03	7.76E + 02
Electricity	MJ/km	Btu/MLF	MJ/km	Btu/MLF
Electricity from other sources	9.59E + 01	2.77E + 04	1.74E + 02	5.04E + 04
Energy from hydro power	2.03E + 03	5.86E + 05	9.93E + 01	2.87E + 04
Water usage at manufacturing facility	kg/km	lb/MLF	kg/km	lb/MLF
Municipal water source	8.18E + 02	5.50E + 02	9.51E + 02	6.39E + 02
Recycled water	2.11E + 00	1.42E + 00	3.81E + 01	2.56E + 01
Well water source	1.88E + 02	1.26E + 02	8.11E + 02	5.45E + 02

[1] Includes burdens for manufacturing LVL and OSB processes.
[2] Tracked separately, wood/waste fuel purchased by LVL and OSB plants.
[3] Tracked separately, wood and bark fuel generated and combusted for heat during LVL and OSB manufacturing.

tained from the U.S. Department of Energy (USDOE) for the year 2000 (USDOE 2001). In the PNW, the dominant form of energy is hydro, making up 74.3% of the total. In the SE, the dominant form of fuel for electricity is coal at 45.6% followed by natural gas (23.0%) and nuclear (21.6%), respectively. In the SimaPro (LCI) software using the Franklin database, no burdens are assessed for hydroelectricity generation, but considerable burdens are associated with the combustion of coal and other fossil fuels, as well as for nuclear power generation.

TABLE 6. *Breakdown of generation of electricity by fuel sources as defined by USDOE (2001).*

Fuel source	Percentage share, 2000	
	PNW	SE
Coal	8.1	45.6
Petroleum	0.3	4.5
Natural gas	12.3	23.0
Nuclear	4.0	21.6
Hydro	74.3	1.8
Other	1.1	3.5
Total	100	100

The energy use for manufacturing I-joist can be represented in a number of ways: 1) the actual energy use for the I-joist production facility (referred to as the site energy use), 2) the allocated energy to I-joist for the site (allocated site energy use), and 3) the allocated energy for the cumulative system boundary that includes energies to produce OSB, plywood, I-joist, and all resins (allocated cumulative energy use). Table 7 provides both site scenarios and is based on the input fuels and electricity in Table 3 and the allocation factors in Table 2. The energies for the fuels are based on their higher heating values (HHV) and the electricity as 3.6 MJ/kWh and do

TABLE 7. *Fuel and electricity energy[1] use at the I-joist plant site; both unallocated and allocated to I-joist on a mass basis.*

	Unallocated energy use at I-joist plant				Allocated energy use at I-joist plant			
	PNW on-site energy		SE on-site energy		PNW on-site energy		SE on-site energy	
	MJ/km	Btu/MLF	MJ/km	Btu/MLF	MJ/km	Btu/MLF	MJ/km	Btu/MLF
Fuel use								
Natural use	1.76E + 01	5.10E + 02	2.28E + 02	6.59E + 04	1.58E + 01	4.58E + 03	2.12E + 02	6.13E + 04
LPG	5.42E + 01	1.57E + 04	1.26E + 02	3.63E + 04	4.87E + 01	1.41E + 04	1.17E + 02	3.37E + 04
Diesel	3.85E + 01	1.11E + 04	1.40E + 02	4.03E + 04	3.46E + 01	9.99E + 03	1.30E + 02	3.75E + 04
Electrical use								
Electricity	9.93E + 02	2.87E + 05	8.87E + 02	2.56E + 05	8.92E + 02	2.58E + 05	8.25E + 02	2.38E + 05
Total	1.10E + 03	3.18E + 05	1.38E + 03	3.99E + 05	9.91E + 02	2.86E + 05	1.28E + 03	3.71E + 05

[1] Energy values were determined for the fuels using their higher heating values (HHV) in units of MJ/kg as follows: diesel 44.0, liquid petroleum gas (LPG) 54.0, and natural gas 54.4. Electricity was calculated at 3.6 MJ/kWh.

not consider combustion efficiency or line losses. The dominant energy use is electricity, representing 90% and 64% of the total site use for the PNW and SE, respectively. If these energy values are to be compared to those of other products, the same approach of using HHV should be used; otherwise the energies should be recalculated using comparative energy values, eg., lower heating values (LHV).

Table 8 gives the cumulative energy values for the production of I-joist for the cumulative system boundary that includes all impacts for the production of LVL, OSB, resins, and I-joists. The wood fuel, although not used directly in I-joist production, appears because of its use as a fuel for the production of LVL and OSB. Primary fuels of coal, crude oil, natural gas, and uranium appear because they are the fuels used to produce, deliver, and combusted as fuel for production of electricity, and used for the production of products and resin, as well as feedstock for the resins. The energy for electricity that did not have a defined fuel source, hydro and other sources, were taken at their energy value without considering efficiency. The wood fuel represented 47% and 45% of the cumulative energy for production. The SE consumed more energy than the PNW for two reasons: one was the nature of the wood being processed in that more water needs to be dried from the wood, and another was the greater use of fossil fuels and uranium for producing electricity.

LIFE-CYCLE INVENTORY

The life-cycle inventory output for producing I-joists is given in Table 5 for product, co-

TABLE 8. *Allocated, cumulative energy[1] use to produce I-joist.*

	Energy use			
	PNW I-joist		SE I-joist	
Renewable fuel use	MJ/km	BTU/MLF	MJ/km	BTU/MLF
Wood fuel (biomass)[2]	2.07E + 04	5.98E + 06	2.60E + 04	7.52E + 06
Non-renewable fuel use				
Coal	4.06E + 03	1.17E + 06	8.42E + 03	2.43E + 06
Crude oil	4.83E + 03	1.40E + 06	6.01E + 03	1.74E + 06
Natural gas	1.22E + 04	3.52E + 06	1.69E + 04	4.87E + 06
Uranium	3.00E + 02	8.67E + 04	6.19E + 02	1.79E + 05
Electricity use				
Electricity from hydro power	2.04E + 03	5.90E + 05	9.90E + 01	2.86E + 04
Electricity from other sources	9.65E + 01	2.79E + 04	1.75E + 02	5.04E + 04
Total	4.42E + 04	1.28E + 07	5.82E + 04	1.68E + 07

[1] Energy values were determined for the fuels using their higher heating values (HHV) in units of MJ/kg as follows: coal 26.2, crude oil 45.5, natural gas 54.4, and wood oven-dry 20.9. Uranium was calculated at 381,000 MJ/kg and electricity at 3.6 MJ/kWh.

[2] Wood fuel includes both categories of wood fuel and purchased wood/bark waste fuel; oven-dry weight.

product, raw materials, electricity, and water usage, and in Table 9 for emissions to air, water, and land. For a detailed listing of all outputs, see Wilson and Dancer (2004b). The analysis does not include impacts for production and delivery of logs to produce the LVL and OSB, nor the transportation of material to the plywood, OSB, and I-joist plants. The manufacturing of LVL and OSB are included in the cumulative system boundary of this study. The LCI outputs results were generated using SimaPro LCI software with the Franklin database (1999) for fuel use and electricity production burdens for their production. The LCI data for the PRF used PF as a substitute and were from ATHENA™ (1993) and the MDI was from the SimaPro database with Boustead Consulting listed as the data collector (PRe' Consultants 2001). For a complete listing of the LCI inputs and outputs to produce the resins, see Wilson and Dancer (2004b). All other data are based on survey data obtained from manufacturing facilities in each region. The emissions in Table 9 are for producing 1.0 MLF of I-joist in each geographical region and are allocated on a mass basis, based on the fraction of I-joist to the total weight of I-joists and co-products. The allocation for I-joists in the PNW is 89.8% and in the SE it is 93%.

The CO_2 emissions in Table 9 are given in three categories based on their fuel source: combustion of biomass, fossil fuel, and non-fossil fuel that is most likely biomass. The non-fossil fuel data come from the Franklin database for electricity generation. The biomass (wood and bark hogged fuel) comes from the production models for LVL and OSB. Biomass and fossil fuel-generated CO_2 are tracked separately since fossil fuel-generated CO_2 contributes signifi-

TABLE 9. *Life-cycle inventory results for production of I-joists composed of LVL flanges and OSB web; gives allocated cumulative emissions.*

	PNW I-joist		SE I-joist	
	kg/km	lb/MLF	kg/km	lb/MLF
Emissions to air				
Acetaldehyde	1.61E − 01	1.08E − 01	1.62E − 01	1.09E − 01
Acrolein	5.13E − 02	3.45E − 02	5.79E − 02	3.89E − 02
CO	6.96E + 00	4.68E + 00	1.01E + 01	6.82E + 00
CO_2 (biomass)	1.29E + 03	8.66E + 02	1.65E + 03	1.11E + 03
CO_2 (fossil)	8.35E + 02	5.61E + 02	1.42E + 03	9.51E + 02
CO_2 (non-fossil)	2.77E + 01	1.86E + 01	9.24E + 01	6.21E + 01
Formaldehyde	2.68E − 01	1.80E − 01	2.75E − 01	1.85E − 01
MDI (isocyanate)	1.74E − 04	1.17E − 04	1.96E − 04	1.32E − 04
Methane	2.63E + 00	1.77E + 00	3.87E + 00	2.60E + 00
Methanol	6.44E − 01	4.33E − 01	6.92E − 01	4.65E − 01
NO_x	6.12E + 00	4.11E + 00	8.94E + 00	6.01E + 00
Particulates	1.26E + 00	8.49E − 01	1.03E + 00	6.90E − 01
Particulates (PM10)	4.18E − 01	2.81E − 01	2.02E + 00	1.36E + 00
Particulates (unspecified)	3.97E − 01	2.67E − 01	8.21E − 01	5.52E − 01
Phenol	1.85E − 01	1.24E − 01	2.02E − 01	1.36E − 01
SO_2	2.63E − 01	1.77E − 01	2.95E − 01	1.98E − 01
SO_x	1.04E + 01	7.01E + 00	1.61E + 01	1.08E + 01
VOC	3.29E + 00	2.21E + 00	2.83E + 00	1.90E + 00
Emissions to water				
BOD	3.24E − 02	2.18E − 02	3.08E − 02	2.07E − 02
Cl−	4.14E + 00	2.78E + 00	3.21E + 00	2.16E + 00
COD	2.43E − 01	1.63E − 01	2.47E − 01	1.66E − 01
Dissolved solids	1.20E + 01	8.09E + 00	1.70E + 01	1.14E + 01
Oil	2.13E − 01	1.43E − 01	2.99E − 01	2.01E − 01
Suspended solids	3.78E − 01	2.54E − 01	6.56E − 01	4.41E − 01
Emissions to land				
Solid waste	1.08E + 02	7.24E + 01	2.07E + 02	1.39E + 02

cantly to global warming and greenhouse gases, whereas biomass generated CO_2 is considered impact-neutral (EPA 2003). For the production of PNW I-joist, for the cumulative boundary condition that includes production of LVL and OSB, the CO_2 generated as a result of biomass and non-fossil fuel combustion is 61% of the CO_2 cumulative emissions. For LVL produced in the SE region, CO_2 biomass and non-fossil are 55% of the cumulative CO_2 emissions. This high percentage of biomass CO_2 is favorable to the environment, and its high percentage is impressive when considering that the total CO_2 also includes fossil fuel emissions generated from production of electricity and resins.

CARBON BALANCE

The biogenic carbon flow in and out of the I-joist manufacturing process was tracked in a "gate-to-gate" analysis of I-joist production. Wood is considered a storage place for carbon since it is about 50% carbon and for most wood-building products lasts well over 75 years in service (Winistorfer et al. 2005). In order to track carbon in the I-joist process, it was necessary to determine all of the wood-related input elements that contain carbon and the amount of carbon entering the I-joist system. It is important to note that only carbon in wood and the carbon containing emissions that can be attributed to wood were tracked. For the PNW species of wood, carbon was 50.4% of its oven-dry mass, whereas for the SE species of wood, carbon was 48.5% of oven-dry mass. The source of the carbon content of wood is Birdsey (1992).

The two wood-related input elements into the I-joist process are LVL and OSB, while the output consists of I-joist, sawdust, and those emissions related to pressing only since no wood drying or combustion occurred at the site. The input and output values were essentially the same values, which should be the case since the process is relatively simple in regard to tracking material flows. Table 10 gives the biogenic carbon balance through the I-joist manufacturing facilities. Most of the carbon occurs in the product (90% and 93% for PNW and SE, respectively) compared to that stored in the co-product (10% and 7% for PNW and SE, respectively), and an insignificant quantity of carbon, essentially zero occurs in the air emissions. For 1.0 km of I-joist, it stores 1,460 kg and 1,830 kg of biogenic carbon for product produced in the PNW and SE, respectively. It is significant to track this stored carbon since it represents CO_2 removed from the atmosphere and not available for contributing to the greenhouse gases or global warming. For every 1.0 kg of carbon sequestered in wood products it represents 3.67 kg of CO_2 removed from the atmosphere; therefore for every 1.0 km of I-joist there are 5,358 kg and 6,716 kg of removed CO_2 for the PNW and SE, respectively.

CONCLUSIONS

A study was conducted of the life-cycle inventory of the manufacture of wood composite

TABLE 10. *Biogenic carbon balance, tracking flow of wood carbon through the I-joist manufacturing process. Products and co-products are wood only, resin weight was subtracted.*

	PNW		SE	
Substance	kg/km	lb/MLF	kg/km	lb/MLF
Input				
LVL	8.39E + 02	5.64E + 02	1.13E + 03	7.61E + 02
OSB	7.95E + 02	5.34E + 02	8.30E + 02	5.58E + 02
Total	1.63E + 03	1.10E + 03	1.96E + 03	1.32E + 03
Output				
I-joist	1.46E + 03	9.82E + 02	1.83E + 03	1.23E + 03
Co-products	1.67E + 02	1.12E + 02	1.37E + 02	9.21E + 01
Emissions to air	9.60E – 03	6.45E – 03	2.98E – 02	2.00E – 02
Total	1.63E + 03	1.09E + 03	1.97E + 03	1.32E + 03

I-joists. To collect production data of all inputs and outputs from the plants, surveys were conducted in 2000 of two plants in each of two major production regions of the U.S., the Pacific Northwest and Southeast. The production of these plants represents 33% and 27% of total production for PNW and SE regions, respectively. The data were found to be of high quality based on comparisons of data between plants and regions, and upon mass and energy balances. Input data consisted of fuels, electricity, life-cycle inventories for LVL and OSB, and resins, while outputs consisted of I-joist, sawdust a co-product, and emissions to air, water, and land.

The cumulative boundary system looked at the environmental impacts of manufacturing I-joists from the logs delivered to the LVL and OSB production facilities through their production into I-joists. The LCI data for I-joists are presented on a production unit of 1.0 km and 1.0 MLF (one thousand linear feet), the U.S. industry product unit. The impact considered those impacts including the production and delivery of electricity and fuel, and the production of resin. Transportation distances of materials to the plants are given. To obtain a cradle-to-gate LCI analysis for I-joists, the LCI data for logs, and the transportation of logs, materials, LVL, OSB, and resins based on available mileage would have to be added to the gate-to-gate LCI data provided in this study.

Energy use for manufacturing I-joist for the cumulative boundary system does not dominate at the production site, rather it is the energy and electricity use for the manufacture of LVL, OSB, and resins that dominate. The allocated site energy is only about 1% to 2% of the cumulative energy use. This energy use would be greater if green veneer were used as input to the I-joist process. The environmental impact likewise is relatively small for manufacturing of I-joists at the site with only small amounts of natural gas, LPG, diesel, and electricity used, whereas for the manufacture of LVL, OSB, and resins, larger amounts of wood and fossil fuels, and electricity are used. Energy generated by the combustion of wood fuels for the PNW and SE regions respectively represents 47% and 45% for the cumulative boundary condition. The wood fuel (biomass fuel) and other non-fossil fuels contribute 61% and 47% of total CO_2 for the PNW and SE regions, respectively. This is beneficial in that the wood-derived CO_2 is considered to have a neutral impact on global warming and greenhouse gases in that it can be up taken by the forest ecosystem, storing carbon in the wood and releasing oxygen to the atmosphere. Combustion of fossil fuels, unlike that for biomass, generates CO_2 that contribute to both global warming and greenhouse gases. Energy to produce the electricity varied significantly between the two regions, with the PNW heavily dependent upon hydro generation, while the SE was dependent upon coal, oil, natural gas, and nuclear fuels. Resins used to bond the LVL, OSB, and the I-joists were also dependent upon fossil fuels for both energy and feedstock.

Carbon studies were conducted to track carbon from the input materials through processing to produce I-joist, co-product, and emissions. Only carbon related to wood was tracked since this sequestered carbon could be seen as avoiding the formation of CO_2 that could be released to the atmosphere. Wood-based materials are about 50% carbon, whether it is in a product such as I-joist or as co-product such as sawdust that most likely was converted into other wood products such as particleboard. For every 1.0 km of I-joist, there are 5,380 kg and 6,716 kg of CO_2 removed from the atmosphere by PNW and SE product, respectively.

The LCI data for wood composite I-joists are made available for public access through this publication and the U.S. LCI Database Project, which is a database for all major materials and manufacturing processes in the U.S. (NREL 2005).

ACKNOWLEDGMENTS

This research project would not have been possible without the financial and technical assistance provided by the USDA Forest Service, Forest Products Laboratory (JV1111169-156), DOE's support for developing the research plan (DE-FC07-961D13437), CORRIM's University membership, and the contributions of many companies. Our special thanks are extended to those companies and their employees that participated in the surveys to obtain production data. Any opinions, findings, conclusions, or recommendations expressed in this article are those of the authors and do not necessarily reflect the views of the contributing entities.

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