Proceedings of the 58th International Convention of Society of Wood Science and Technology
June 7-12, 2015 - Grand Teton National Park, Jackson, Wyoming, USA

Life-Cycle Inventory Analysis of I-joist Production in the United States

Richard D. Bergman [1*]

[1] Research Forest Product Technologist
U.S. Forest Service Forest Products Laboratory, Madison, Wisconsin, USA
* *Corresponding author*
rbergman@fs.fed.us

Abstract

Documenting the environmental performance of building products is becoming increasingly common. Creating environmental product declarations (EPDs) based on life-cycle assessment (LCA) data is one approach to provide scientific documentation of the products' environmental performance. Many U.S. structural wood products have LCA-based "eco-labels" developed under the ISO standard 14025. In this study, the standard dictates underlying life-cycle inventory (LCI) data to be used reflect current practices in the industry. Therefore, gate-to-gate manufacturing LCI data for I-joist must be developed to construct updated cradle-to-gate LCAs for southeastern (SE) and for Pacific Northwestern (PNW) regions of the United States. Modeling the production weighted-average primary industry data per 1.0 km of I-joists with an assumed average depth of 30 cm through LCI analysis provides cumulative energy consumption and environmental outputs. For PNW and SE, cumulative mass allocated energy consumption associated with manufacturing 1.0 km of I-joist was found to be 65.7 and 71.0 GJ/km, respectively, with about 30% of the primary energy provided from wood residues. Emission data produced through modeling found that estimated biomass and fossil CO_2 emissions in kg/km were, respectively, 1,774 and 1,969 for the PNW and 1,808 and 2,042 for the SE. One km (4,437 oven-dry kg wood portion, on average) of I-joist stores about 8,130 kg CO_2 equivalents. The amount of carbon stored in I-joists thus exceeds total CO_2 emissions during manufacturing by about 215%. From this study, the gate-to-gate I-joist manufacturing LCI data can now be incorporated into the cradle-to-gate LCAs to develop an updated EPD.

***Keywords*: ** environmental product declaration, life-cycle inventory, I-joists, life-cycle analysis, LCA, wood, structural composite lumber

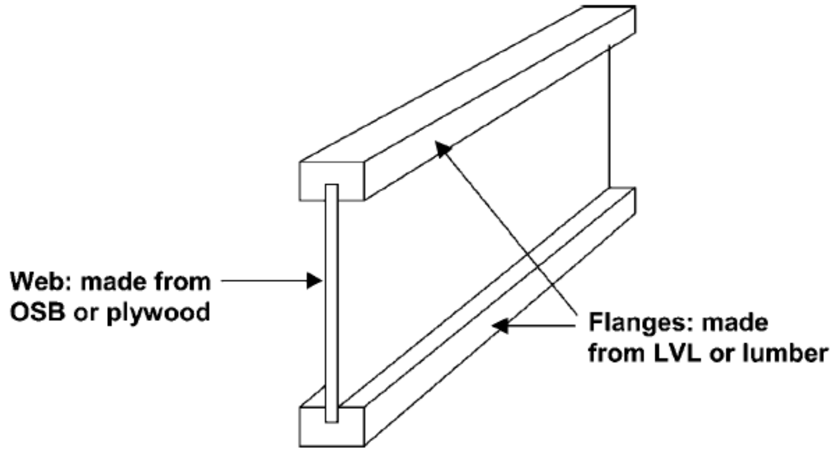
Introduction

Documenting the environmental performance of building products is becoming widespread because green building programs and concerns that some green-marketing claims are misleading (i.e., green-washing). Developing environmental product declarations (EPDs) for building products is one way to provide scientific documentation and to counter green-washing (Bergman and Taylor 2011). In addition, EPDs are increasingly being required in green building rating systems and building codes. Life-cycle inventory (LCI) data are the underlying data for subsequent development of life-cycle assessments (LCAs) and EPDs. EPDs are similar to nutritional labels for food. The LCI was in conformance with the Product Category Rules (PCR) for North American Structural and Architectural Wood Products (FPInnovations 2013) and ISO 14040/14044 standards (ISO 2006a, b). This report follows data and reporting requirements as outlined in the PCR and contains the LCI components for producing a North American EPD (ISO 2006c; FPInnovations 2013).

LCI compiles all raw material and energy inputs and environmental outputs associated with the manufacture of a product on a per-unit basis within carefully defined system boundaries. These boundaries can be limited to only one stage within the product lifecycle (e.g., gate-to-gate). Multiple sequential LCI stages are usually combined in an LCA. LCAs describe the total environmental impact for a particular product, referred to either as cradle-to-gate (raw material extraction to mill gate output) or as cradle-to-grave (raw material extraction to waste disposal) analysis.

Description of I-joists

Many engineered structural wood products have been developed in the last several decades, eg, I-joists (Fig 1). An I-joist is comprised of a web made from structural wood panel, mostly oriented strandboard (OSB) and some plywood. The web is glued between two flanges made from solid-sawn or finger-jointed lumber, but mostly laminated veneer lumber (LVL) (USEPA 2002; Wilson and Dancer 2005; Stark et al. 2010; ASTM 2013). I-joists have an “I” shape form and are measured in linear feet in the United States. Production values and study results were reported per linear km with an assumed average depth of 30 cm. I-joist depth varies notably, but large quantities of I-joists made in the United States have a depth of 30 cm. These engineered structural wood products are designed to be used in the same manner as solid wood products such as sawn lumber but with different properties.



Source (Wilson and Dancer 2005) Society of Wood Science and Technology

Figure 1. I-joist.

Goal

The goal of this paper is to document the gate-to-gate LCI of I-joist manufacturing for Pacific Northwest (PNW) and Southeast (SE) United States as part of a cradle-to-gate LCA. The paper documents material flow, energy type and use, emissions to air and water, solid waste production, and water impacts for the I-joist manufacturing process per 1.0 km. Primary mill data were collected through a survey questionnaire mailed to I-joist plants. This survey tracked raw material inputs (including energy), product and byproduct outputs, and emissions within the cut-off rules and system boundary definition to water, air, and land. An industry-standard production unit (i.e., reference unit) was incorporated that can be translated to a metric production unit. Secondary data, such as pre-mill gate processes (e.g., wood and electricity production), were drawn from peer-reviewed literature per CORRIM guidelines (CORRIM 2010). Material and energy balances were calculated from primary and secondary data. Using these material and energy data, the environmental outputs were estimated by modeling using the software package SimaPro 8 (Pré Consultants 2015), which follows internationally accepted standards and uses the U.S. LCI Database (NREL 2012).

A large sample is required to attain results that are representative of the I-joist industry. CORRIM (2010) protocol targets a minimum of 5% of total production with preferred percentage of 20% for an industry such as the I-joist industry with relatively few manufacturers.

Method

Scope

This study covered the manufacturing stage of I-joist from web and flange components to final product leaving the mill according to ISO 14040 and 14044 standards (ISO 2006a,b; ILCD 2010; FPInnovations 2013). Impacts from (offsite) oriented strandboard (OSB), laminated veneer lumber (LVL), plywood, softwood plywood, and finger-jointed lumber production were included in the analysis (Kline 2005; Wilson and Sakimoto 2005; Bergman 2015; Milota et al. 2005). New data, once developed, will be incorporated into the cradle-to-gate I-joist LCA. OSB and plywood made up the web materials whereas LVL and finger-jointed lumber comprised the flange materials. Data for dry planed softwood lumber acted as a proxy for finger-jointed lumber. Because finger-jointed lumber has additional processing from cutting and gluing compared to solid-sawn lumber, the emission estimates shown in the present study will likely be lower than if finger-jointed lumber data were incorporated. The manufacturing stage LCI was the result of a gate-to-gate analysis of cumulative energy of manufacturing and transportation of raw materials.

Selecting an allocation approach is a vital part of a LCI study. In the present study, all primary energy and environmental outputs were assigned by mass allocation. The decision was justified by the understanding that the wood residues are coproducts with a value rather than a waste material.

Industry data

Five U.S. I-joist plants representing 57.7% of 2012 U.S. I-joist production (63,135 km) provided primary data for the PNW and SE (APA 2014). Total U.S. I-joist production for 2012 was 109,387 km. The surveyed plants provided detailed annual production data on their facilities, including on-site fuel consumption, electrical usage, web and flange volumes, and I-joist production for 2012. A previous 2000 U.S. I-joist LCI study was performed by Wilson and Sakimoto (2005) that covered 33% and 27% of production in the PNW and SE, respectively. Production data for I-joist by region are no longer available.

Declared unit

The present study selected a declared (reference) unit of 1.0 (linear) km of I-joist with an assumed average depth of 4.8 cm. For conversion from the U.S. industry measure, 1 km equals 3.281 thousand ft. Cumulative energy consumption and LCI flows were reported per 1.0 km of the final product, I-joist.

System boundary

The defined system boundary determined the unit processes to include and standardized material flows, energy use, and emission data. The cumulative system boundary is shown by the solid line in Fig 2 and includes both on- and off-site emissions for all material and energy consumed. Three main unit processes exist in manufacturing I-joist: (1) routing and shaping of web and flanges, (2) assembly of I-joists, and (3) sawing and curing with energy generation as an auxiliary process (USEPA 2002; Wilson and Dancer 2005). All emissions (i.e., environmental outputs) and energy consumed were assigned to the I-Joist and co-products (i.e., sawdust) by mass.

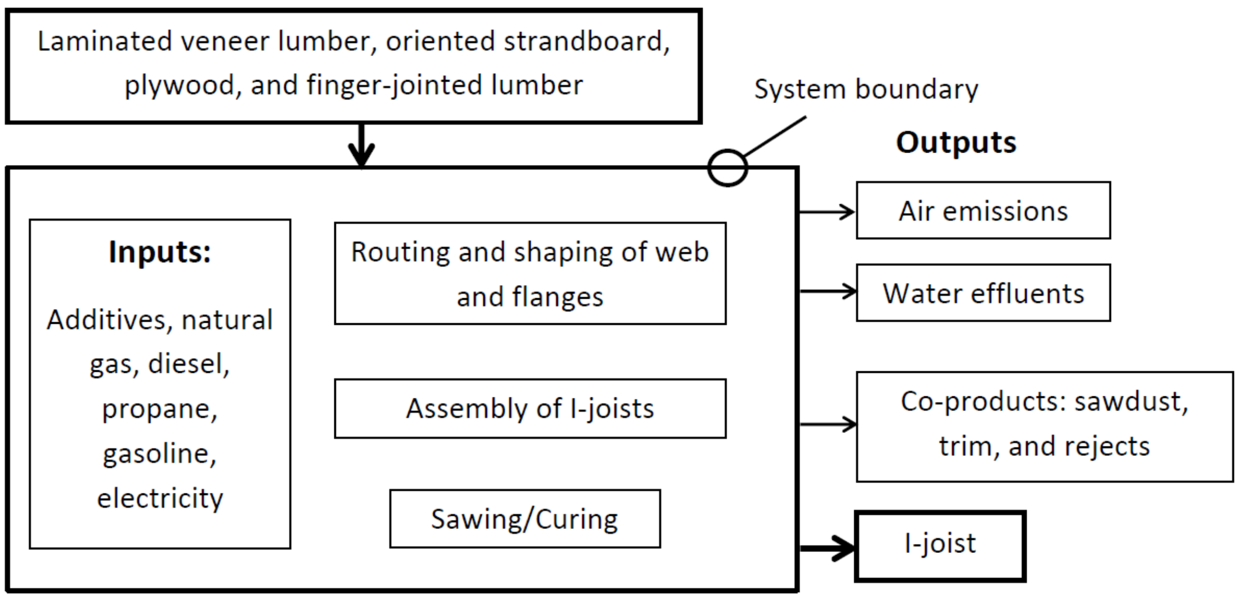


Figure 2. System boundary for I-joist manufacturing life-cycle stage

Fuel resources used for the cradle-to-gate production of energy and electricity were included within the cumulative system boundary. Off-site emissions include those from grid electricity production, transportation of feedstock and additives to the plant, and fuels produced off-site but consumed on-site. Ancillary material data such as motor oil, paint, and hydraulic fluid were collected and were part of the analysis.

Results and Discussion

Five I-joist plants provided detailed primary data on mass flow, energy consumption, fuel types, and air emissions. Primary data were weight-averaged based on each mill's production volume and modeled using LCA modeling software to estimate cumulative energy consumption and environmental outputs expressed on a per 1-km unit basis with an assumed depth of 30 cm.

Energy inputs

Weighted-average energy inputs consumed on-site at the I-joist manufacturing site were developed from survey data (Table 1). Electricity and natural gas were the primary energy inputs at 378 kWh and 36 m^3 for the PNW and 312 kWh and 41 m^3 for the SE per linear km of I-joist. Primary energy is energy embodied in the original resources such as crude oil and coal before conversion (e.g., combustion). Thus, PNW I-joist manufacturing consumed more electricity but less natural gas. The production-weighted coefficient of variation (CoVw) showed the large variation for natural gas consumption for the PNW with a value of 103%, although consumption per km of final product was somewhat similar to the SE value of 41 m^3.

Table 1. Weighted-average on-site energy inputs for I-joist manufacturing per km

	Pacific Northwest			Southeast		
	Quantity	Unit	CoVw[a] (%)	Quantity	Unit	CoVw[a] (%)
Energy inputs						
Electricity	378	kWh	35%	312	kWh	20%
Natural gas	36	m^3	103%	41	m^3	49%
Diesel	2.99	L	76%	4.77	L	16%
Propane	3.87	L	4.7%	4.73	L	5.3%
Gasoline	0.054	L	–	0.217	L	141%

[a] Production-weighted coefficient of variation.

Material

To evaluate data quality, a mass balance was performed including additives (Table 2). For the material inputs, LVL, OSB, plywood, and finger-jointed lumber usage were 2,318, 1583, 1033, and 797 oven-dry (OD) kg for the PNW and 2,597, 2,212, 0, and 28 OD kg for the SE plants, respectively, to produce 1.0 km of I-joists. Final mass of the PNW I-joist was heavier at 5,381 OD kg compared to 4,415 OD kg for SE with a weighted average of 4,930 OD kg/km. Phenol-resorcinol-formaldehyde (PRF) resin was the largest component of the additives used to glue the I-joist together as a single unit followed by a hardener. A large difference is noted in between the regions and the large variance for additive consumption in the SE region, up to 141%.

Table 2. Mass balance of I-joist manufacturing per km

	Pacific Northwest			Southeast		
	(OD kg)	Mass (%)	CoVw[a] (%)	(OD kg)	Mass (%)	CoVw[a] (%)
Feedstocks	INPUTS			INPUTS		
Laminated veneer lumber	2318	40.2%	58%	2597	53.7%	2.4%
Oriented strandboard	1583	27.5%	3.6%	2212	45.7%	7.0%
Plywood	1033	17.9%		0	0.0%	
Lumber, finger-jointed[b]	797	13.8%	162%	28	0.6%	
TOTAL, FEEDSTOCK	5731	99.5%	19.0%	4809	99.4%	2.2%
Additives						
Phenol-resorcinol-formaldehyde resin	13.8	0.2%	71.4%	33.5	0.7%	141%
Phenol-resorcinol resin	1.9	0.0%	245%	0.0	0.0%	
Aqueous emulsion polymer	0.0	0.0%		1.5	0.0%	141%
Polyurethane polymer	0.0	0.0%		0.3	0.0%	141%
Hardener	9.0	0.2%		0.5	0.0%	141%
Catalyst	2.0	0.0%	157%	0.0	0.0%	
TOTAL, ADDITIVES	25	0.4%	47.1%	36	0.7%	46.2%
TOTAL, IN	5760	100%		4840	100%	
Products	OUTPUTS			OUTPUTS		
I-joist	5381	93.4%	21.9%	4415	91.2%	4.6%
Co-Products						
Sawdust, sold	363	6.3%	99%	411	8.5%	18%
Sawdust, wood fuel	0	0.0%		1	0.0%	141%
Panel trim. Sold	2	0.0%		17	0.4%	141%
Rejects	10	0.2%		0	0.0%	
TOTAL, CO-PRODUCTS	374	6.5%	98%	428	8.8%	46%
TOTAL, OUTPUTS	5760	100%		4840	100%	

[a] Coefficient of variation, production-weighted.
[b] Used dry planed lumber as proxy.

Cumulative energy consumption

Cumulative energy consumption for manufacturing I-joist was 65.7 and 71.0 GJ/km for the PNW and SE, respectively, with wood fuel accounting for about 30% (Table 3). Listed values include impacts from manufacturing the wood components (i.e., flanges and web). Wood residues and natural gas were the two most important energy resources followed closely by crude oil and coal. Most of the wood fuel was consumed before the I-joist manufacturing stage where drying the wood was accomplished via steam boilers fueled primarily by wood and not fossil fuels. In addition, consumption of natural gas on-site at the I-joist manufacturing facilities was for curing the resins applied during assembly of the I-joist. Natural gas and coal are also the two primary sources of energy to fuel the U.S. electricity grid. Therefore, natural gas is the largest fossil fuel input for making I-joist for both regions.

Table 3. Cumulative energy (higher heating values (HHV)) consumed during production of I-joist—cumulative, mass allocated, gate-to-gate LCI values[a]

	Pacific Northwest			Southeast		
Fuel[b,c]	(kg/km)	(MJ/km)	(%)	(kg/km)	(MJ/km)	(%)
Wood fuel	995	20,809	31.7	1014	21,208	29.9
Natural gas[d]	300	16,330	24.9	345	18,786	26.5
Crude oil[d]	274	12,452	19.0	489	12,803	18.0
Coal[d]	427	11,183	17.0	285	12,972	18.3
Uranium[d]	0.00635	2,419	3.7	0.01332	5,075	7.1
Hydro	-	2,252	3.4	-	149	0.2
Energy, other	-	249	0.4	-	4	0.0
Total		65,690	100		70,990	100

[a] Includes fuel used for electricity production and for log transportation.
[b] Values are unallocated and cumulative and based on higher heating values.
[c] Energy values were found using their HHV in MJ/kg: 20.9 for wood oven-dry, 26.2 for coal, 54.4 for natural gas, 45.5 for crude oil, and 381,000 for uranium.
[d] Materials as they exist in nature and have neither emissions nor energy consumption associated with them.

Wood products typically consume more energy during the manufacturing life-cycle stage than any other stage (Puettmann and Wilson 2005; Winistorfer et al. 2005; Puettmann et al. 2010). To compare with an earlier CORRIM study on making 1.0 km of I-joist in the PNW and SE regions of the United States, cumulative allocated energy consumptions are 44.2 and 58.2 GJ/km (Wilson and Dancer 2005). The values listed in Wilson and Dancer (2005) use mass allocation. As stated previously, this study allocates by mass.

Carbon

Carbon content for wood products is assumed to be 50% by mass of OD wood. Wood makes up about 90% of final product. Therefore, the carbon stored in the wood portion of 1.0 km (2,218 OD kg) of I-joist when completely decomposed is equivalent to 8,130 kg of CO_2[1] released directly to the atmosphere. Stating it another way, the CO_2 value is equivalent to the CO_2 removed from the atmosphere during tree growth and now stored in the final product.

[1] 4,437 OD kg wood * (0.5 kg carbon/1.0 OD kg wood) * (44 kg CO_2/kmole/12 kg carbon/kmole) = 8,130 kg CO_2

Emissions

Table 4 lists allocated environmental outputs for manufacturing 1.0 km of I-joist for the cumulative system boundaries for the PNW and SE, respectively. Emission data produced through modeling found that estimated biomass and fossil CO_2 emissions in kg/km were 1,774 and 1,969 for PNW and 1,808 and 2,042 for SE. Therefore, the amount of carbon stored in 1.0 km of I-joist, 8,130 kg is about 215% of the total CO_2 emissions released during manufacturing. For on-site energy use, burning natural gas to cure the I-joist was the main source of fossil CO_2. Major sources of air emissions were from hot pressing and from the energy generation auxiliary process that includes grid electricity (off-site) and boiler operations (on-site). Notable, most of nitrogen oxides (NOx) released, about 98% was derived from the production of PRF resin for I-joists and LVL manufacturing and the production of slack wax for OSB manufacturing.

Table 4. Cumulative environmental outputs for producing one km of I-joist—cumulative, mass allocated gate-to-gate

	Pacific Northwest	Southeast
Substance	(kg/km)	
Water effluents		
BOD5 (Biological oxygen demand)	0.412	0.440
Chloride	81.4	86.77
COD (Chemical oxygen demand)	0.772	0.852
DOC (Dissolved organic carbon)	3.54E-03	5.06E-03
Oils, unspecified	4.84E-02	5.20E-02
Suspended solids, unspecified	104	111
Industrial waste[a]		
Wood waste, to recycling	484	472
Solid waste[b]	74	26
Air emissions		
Acetaldehyde	0.184	0.199
Acrolein	1.54E+00	7.17E-02
Benzene	9.70E-04	8.56E-04
CO	5.96E+00	6.13E+00
CO_2 (biomass (biogenic))	1,774	1,808
CO_2 (fossil)	1,969	2,042
CH_4	5.99E+00	7.24E+00
Formaldehyde	3.29E-01	3.23E-01
Mercury	1.97E-05	2.13E-05
Methanol	8.62E-01	8.01E-01
Nitrogen oxides	94.3	154.0
Non-methane VOC	5.23E-01	5.13E-01
Particulate (PM10)	4.69E-01	4.78E-01
Particulate (unspecified)	5.83E+00	8.27E+00
Phenol	1.54E-01	1.73E-01
Propanol	5.12E-05	5.22E-05
SO_x	2.24E-03	2.20E-03
VOC	5.83E+00	4.60E+00

[a] Includes solid materials not incorporated into the product or co-products but left the system boundary such as bark recycled into mulch.
[b] Solid waste was boiler ash from burning wood. Wood ash is typically used a soil amendment or landfilled.

Conclusions

EPDs provide life-cycle data in a concise and consistent format to enable industry to communicate with customers. This study provides the underlying gate-to-gate LCI data for updating the North American I-joist EPD. Future efforts will incorporate the LCI data into a cradle-to-gate LCA and eventually into an EPD for I-joist.

Structural wood products such as I-joist used in building construction can store carbon for long periods, which is typically greater than the carbon dioxide emissions released during manufacturing (Puettmann and Wilson 2005; Bergman and Bowe 2010; Puettmann et al. 2010). For instance, the present study showed that the amount of carbon stored in I-joists, 9,610 kg/km would be equivalent to more than 215% of the carbon dioxide emissions released during manufacturing if the carbon stored in the final product was released directly to the atmosphere. This approximation held true regardless of where the I-joists were made. In addition, the CO_2 value of 9,610 kg now stored in the final product as carbon is equivalent to the CO_2 removed from the atmosphere during tree growth.

Acknowledgement

I gratefully acknowledge the financial assistance provided by the USDA Forest Service Research and Development that funded this research through CORRIM, cooperative agreement #13-CO-11111137-014. In addition, I appreciate the reviews provided by James Salazar (Athena Sustainable Material Institute), Indroneil Ganguly (University of Washington), and Adam Robertson (Canadian Wood Council).

References

APA (2014) Engineered wood statistics: Third quarter 2014. APA—The Engineered Wood Association. Tacoma, WA. 9 p.

ASTM (2013) Standard specification for establishing and monitoring structural capacities of prefabricated wood I-joists. ASTM International. West Conshohocken, PA. 33 pp.

Bergman RD, Bowe SA (2010) Environmental impact of manufacturing softwood lumber in northeastern and north central United States. Wood Fiber Sci 42 (CORRIM Special Issue):67-78.

Bergman RD, Taylor A (2011) Environmental product declarations of wood products—An application of life cycle information about forest products. Forest Prod J 61(3):192–201.

Bergman RD (2015) Life-cycle inventory analysis of laminated veneer lumber production in the United States. In: Proceedings, Society of Wood Science and Technology 58th International Convention. June 7-12, 2015. Jackson Hole, Wyoming. (*In press).*

CORRIM (2010) Research guidelines for life-cycle inventories. Consortium for Research on Renewable Industrial Materials (CORRIM), Inc., University of Washington, Seattle, WA. 40 pp.

FPInnovations. (2013) Product Category Rule (PCR): For preparing an Environmental Product Declaration (EPD) for North American Structural and Architectural Wood Products. UN CPC 31. NAICS 21. 17 pp. https://fpinnovations.ca/ResearchProgram/environment-sustainability/epd-program/Documents/wood-products-pcr-version-v1.1-may-2013-lastest-version.pdf. (22 April 2015).

ILCD (2010) International Reference Life Cycle Data System (ILCD) Handbook - General guide for Life Cycle Assessment—Detailed guidance. EUR 24708 EN. European Commission–Joint Research Centre–Institute for Environment and Sustainability. Luxembourg. Publications Office of the European Union. 417 pp.

ISO (2006a) Environmental management—life-cycle assessment—principles and framework. ISO 14040. International Organization for Standardization, Geneva, Switzerland. 20 pp.

ISO (2006b) Environmental management—life-cycle assessment—requirements and guidelines. ISO 14044. International Organization for Standardization, Geneva, Switzerland. 46 pp.

ISO (2006c) Environmental labels and declarations—Type III environmental declarations—Principles and procedures. ISO 14025. International Organization for Standardization, Geneva, Switzerland. 25 pp.

Kline ED (2005) Gate-to-gate life-cycle inventory of oriented strandboard production. Wood and Fiber Sci 37(CORRIM Special Issue):74–84.

Milota MR, West CD, Hartley ID (2005) Gate-to-gate life-cycle inventory of softwood lumber production. Wood Fiber Sci 42(Special Issue):47–57.

NREL (2012) Life-cycle inventory database project. National Renewable Energy Laboratory. https://www.lcacommons.gov/nrel/search. (22 April 2015).

PRé Consultants (2015) SimaPro 8 Life-cycle assessment software package. Amersfoort, The Netherlands. http://www.pre-sustainability.com/simapro/. (22 April 2015).

Puettmann ME, Wilson, JB (2005) Life-cycle analysis of wood products: Cradle-to-gate LCI of residential wood building materials. Wood Fiber Sci 37 (Special Issue):18–29.

Puettmann ME, Bergman RD, Hubbard SS, Johnson L, Lippke B, Wagner F (2010) Cradle-to-gate life-cycle inventories of US wood products production—CORRIM Phase I and Phase II Products. Wood Fiber Sci 42 (CORRIM Special Issue):15–28.

Stark NM, Cai Zi, Carll C. (2010) Wood-based composite materials: Panel products, glued-laminated timber, structural composite lumber, and wood–nonwood composite materials. In: Wood handbook—wood as an engineering material. Gen Techn Rep FPL–GTR–113. USDA For Serv Forest Products Laboratory, Madison, WI. pp. 11-1–11–28.

USEPA (2002) AP 42 Section 10.9 Engineered wood products manufacturing. United States Environmental Protection Agency. pp. 10.9-1–24. http://www.epa.gov/ttnchie1/ap42/ch10/final/c10s09.pdf. (22 April 2015)

Wilson JB, Sakimoto ET (2005) Gate-to-gate life-cycle inventory of softwood plywood production. Wood Fiber Sci 37 (Special Issue):58–73.

Wilson JB, Dancer ER (2005) Gate-to-gate life-cycle inventory of I-joist production. Wood Fiber Sci 37 (Special Issue):114–127.

Winistorfer P, Chen Z, Lippke B, Stevens N (2005) Energy consumption and greenhouse gas emissions related to use, maintenance, and disposal of a residential structure. Wood Fiber Sci 37 (Special Issue):128–139.