Cradle-to-Gate Life-Cycle Assessment of Composite I-Joist Production in the United States*

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Abstract

Transparency of environmental impacts for building products is of increasing concern. For wood building products, updating life-cycle assessment (LCA) data are critical to ensure that the corresponding environmental product declarations are of the proper recency to maintain this transparency. This study focused on the developing up-to-date life-cycle inventory (LCI) and associated life-cycle impact assessment (LCIA) data for composite I-joist production in the Southeast (SE) and Pacific Northwest (PNW) regions of the United States. Components of the I-joist production system included in the analysis were laminated veneer lumber (LVL), finger-jointed lumber (FJL), and oriented strandboard (OSB), while the study itself considered five life-cycle stages, including forestry operations and I-joist manufacturing, in addition to the production of the components. Primary 2012 production data were collected and analyzed, and the resultant LCI flow and LCIA results were modeled on a declared unit of 1 km. The cradle-to-gate primary energy consumption was 82.0 and 74.2 GJ/km for all five life-cycle stages in the SE and PNW, respectively. The LVL stage had the highest share at 55 percent (SE) and 51 percent (PNW), followed by OSB and I-joist, while the contribution of forestry operations was minor. The global warming (GW) impact from gate-to-gate I-joist production in the SE, about 59 percent, was attributed to resin inputs and electricity consumption. The main reasons for relatively high GW impacts for LVL and I-joist production were that little wood fuel was available on-site to provide thermal energy for processing and the consumption of natural gas and electricity to aid in emission control.

With the increasing environmental concerns and consumer preference of eco-friendly products, manufacturers are required to differentiate their products by improving the environmental performance of their products and services. Currently, it is common for manufacturers to develop environmental product declarations (EPDs) to address the environmental concerns associated with their products by providing independently verified, comparable and objective information (International Organization for Standardization [ISO] 2006a, Bergman and Taylor 2011). Environmental product declaration is a life-cycle assessment (LCA)–based report where developing wood product life-cycle inventory (LCI) and constructing LCAs helps provide valuable information for the development of EPDs for wood products. In addition, developed LCAs can also be incorporated into creating whole building LCAs for environmental footprint software, such as the Athena Impact Estimator for Buildings (Athena Sustainable Material Institute 2016), or green building certification systems, such as LEED v4, Green Globes, and the ICC-700 National Green Building Standard (Ritter et al. 2011).

A composite I-joist is a structural wood product that is classified under engineered wood products in North American Industry Classification System (NAICS) Code 321213, ‘‘Engineered Wood Member (except Truss) Manufacturing,’’ and is used in structural applications (US

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Census Bureau 2012, ASTM International 2014a). I-joists have an I-shape form and are measured in linear feet in the United States. A composite I-joist is composed of a web made from structural wood panel and two flanges. The web structure used is commonly an oriented strandboard (OSB) and sometimes plywood, while the flanges are made from solid-sawn or finger-jointed lumber (FJL) but more commonly from laminated veneer lumber (LVL; US Environmental Protection Agency [US EPA] 2002; Wilson and Dancer 2004a, 2005a; Stark et al. 2010; ASTM International 2014a). There are many different dimensions of composite I-joists but the most common are dimensions that directly replace 50.8 by 254-mm (2 by 10-in.) and 50.8 by 304.8-mm (2 by 12-in.) structural lumber.

This article presents the cradle-to-gate environmental impacts associated with the production of composite I-joist for the Southeast (SE) and Pacific Northwest (PNW) regions of the United States based on current manufacturing practices. This study was performed as a part of the Consortium on Research for Renewable Industrial Materials (CORRIM) initiative to update LCIs for the major wood products in the United States. Previous CORRIM research has covered nine major forest products, including both structural and nonstructural uses, and four major regions (CORRIM 2005, 2010). This study updated the industry-average composite I-joist production LCI data in the SE and PNW regions of the United States originally developed by Wilson and Dancer (2005a). In addition, LCAs were performed using the updated I-joist LCI data sets.

Materials and Methods

The LCI data were generated based on 2012 primary data collected through survey questionnaires filled out by I-joist manufacturing plants in the SE and PNW regions of the United States along with a site visit. The data were collected in accordance with the CORRIM Research Guidelines for developing LCIs, and the LCA performed was in conformance with the Product Category Rule (PCR) for North American Structural and Architectural Wood Products and ISO 14040 and 14044 standards (ISO 2006b, 2006c; International Reference Life Cycle Data System 2010; CORRIM 2014; FPInnovations 2015). The LCA was performed by using SimaPro 8.2 software for system modeling and by applying the TRACI 2.1 impact assessment method (Bare 2011, PRé Consultants 2016). Complete details of this study for LCI development for I-joist production and the CORRIM project can be found in Bergman and Alanya-Rosenbaum (2017a, 2017b).

Goal and scope definition

The goal of the study was to update cradle-to-gate LCI of I-joist manufacturing for the SE and PNW regions of the United States. For this purpose, gate-to-gate LCI of I-joist manufacturing was generated using up-to-date primary data based on 2012 manufacturing. In addition, the cradle-to-gate environmental impacts associated with I-joist production were quantified through LCA using the developed LCI. The two updated LCA data sets will be used to update the current North American I-joist EPD (American Wood Council–Canadian Wood Council 2013).

The scope of the present LCA study covered the cradle-to-gate life-cycle stages of I-joist production, including forest resource activities, OSB, LVL, and FJL production and production of the final I-joist product ready for shipping from the plant. Forest resources were evaluated as a stand-alone life-cycle stage, and thus its impact was captured separately. Transportation of feedstock (i.e., OSB, LVL, FJL, and resins) to the I-joist facility were taken into consideration in the analysis.

Allocation procedure

In this study, allocation of the inputs and environmental impacts associated with the system was necessary because coproducts were generated during the I-joist manufacturing in addition to the main product, I-joist. This article presents the results based on mass allocation where primary energy and environmental outputs were assigned to various coproducts by mass. In addition to mass allocation, economic allocation was performed, and results were presented because product category rules suggest using economic allocation for a multioutput process when the difference in revenues is more than 10 percent, as it was for this study (FPInnovations 2015). Use of economic allocation may help us understand and evaluate the environmental impact of wood residue coproducts based on their economic value rather than considering them a waste material.

Functional unit

A declared unit is used in instances where the function and the reference scenario for the whole life cycle of a wood building product cannot be stated (FPInnovations 2015). In accordance with the PCR developed (FPInnovations 2015), the declared unit for I-joist production was 1 km. All input and output data were allocated to the declared unit of product based on the mass of products and coproducts in accordance with ISO 14044 (ISO 2006b). Use of a linear measurement unit is consistent with industry practice in the United States, where the production is measured in linear feet. Linear measurements are used because it is difficult to quantify I-joist production in other forms, such as volume, owing to its shape. The composite I-joists produced and evaluated in this study conformed to ASTM Standard D5055 (ASTM International 2016) and the APA—The Engineered Wood Association (2015). As the analysis did not take the declared unit to the stage of being an installed building product, no service life was assigned.

System boundaries

The cradle-to-grave system boundaries of the I-joist production system are presented in Figure 1. The system boundary included forest resource management activities, OSB, LVL, and FJL production, and I-joist production life-cycle stages. The transportation of OSB, LVL, and FJL and resins to the I-joist facility was accounted for if production occurred off-site because some facilities perform the FJL and LVL production at the same site. Within the system boundaries, the authors considered the transportation of raw material, the impacts resulting from the supply and generation of the off-site energy sources, and the consumption of ancillary material, such as motor oil, waxes, paint, and hydraulic fluid in the analysis.

System investigated

Cradle-to-gate LCI flows for composite I-joist manufacturing were presented by five major life stages: forestry

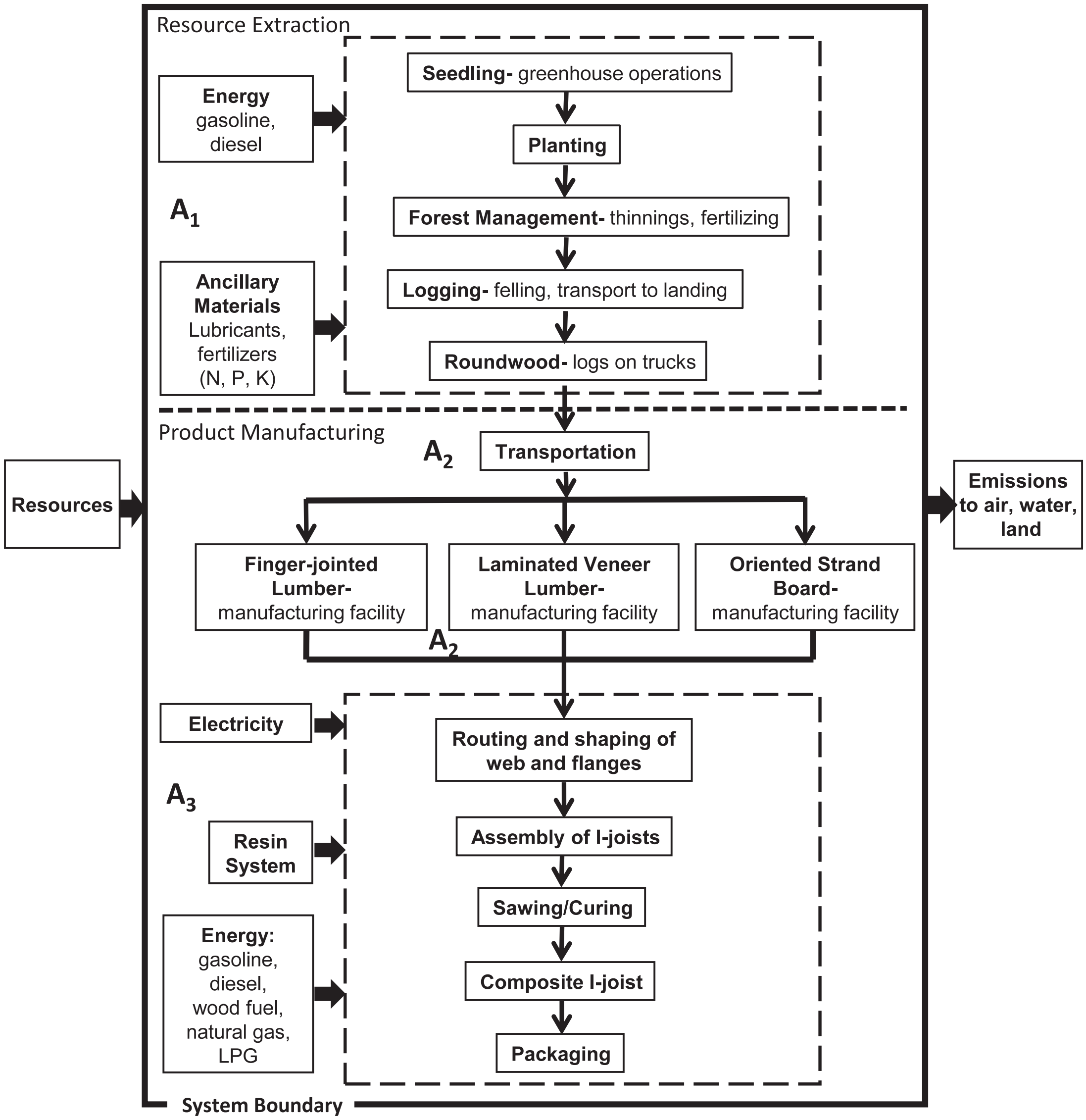

Figure 1.—Cradle-to-gate system boundary and process flow for production of I-joist.

operations, OSB production, FJL production, LVL production, and I-joist production.

Forestry operations.—The forest operations upstream activities include the establishment, growth, and harvest of trees. Forestry operations vary regionally but typically include some combination of growing seedlings, regeneration, site preparation, planting (where applicable), thinning, fertilization (where applicable), and final harvest (Johnson et al. 2005). Harvesting includes felling, skidding, processing, and loading for both commercial thinning and final harvest operations. The primary output product is a log used as feedstock for softwood veneer or plywood, OSB, and lumber production. The coproduct, nonmerchantable (logging) slash, is generally left at a landing. In this study, slash disposal was not modeled, as it was assumed to decay in situ. Forest operations modeled as inputs to production processes were based on forest resource LCI data inputs from the SE and PNW softwood forests (Johnson et al. 2005; Puettmann et al. 2013c, 2013d).

Laminated veneer lumber.—LVL is used as feedstock for composite I-joist manufacturing. Three main processes occur at LVL production: lay-up, hot pressing, and trimming and sawing. Dry veneers and resins are the primary raw materials consumed for the production of LVL, and their cradle-to-gate production is included in the LVL production life stage. For detailed information on the production of LVL, see Wilson and Dancer (2004b, 2005b) and Bergman and Alanya-Rosenbaum (2017c, 2017d, 2017e). One thing to note is that Bergman and Alanya-Rosenbaum (2017c, 2017d, 2017e) broke out dry veneer and LVL production into separate life-cycle stages to aid in identifying environmental hot spots for only LVL production, which is different from this study, where the authors grouped together LVL and dry veneer production and its associated impacts into a single life-cycle stage: LVL production. Thus, the impacts shown here will be higher than for LVL production because of the grouping than what was shown in Bergman and Alanya-Rosenbaum (2017c, 2017d, 2017e). This was conducted for simplicity.

OSB process.—Components for the composite I-joist manufacturing include OSB. Chips and resins are the primary raw materials consumed for the production of OSB. The LCI data from Kline (2005) and Kaestner (2015) were used for modeling the OSB manufacturing.

FJL production.—In FJL production, finger joints are machined on both ends of softwood lumber with special cutter heads. A structural resin, such as melamine-urea-formaldehyde, is applied, and the joints in successive boards are coupled. The resin is cured with the joint under end pressure and heat typically provided by a continuous radio-frequency curing system for this step.

MDI resin.—Methylene diphenyl diisocyanate (MDI) resin is used in the production of I-joists. The LCI for the production of MDI resin was based on a cradle-to-gate study of plastic resins and polyurethane precursors completed by Franklin Associates in 2010 (Franklin Associates 2011). Franklin Associates collected primary data for MDI production, including data on the following MDI precursors: olefins, benzene, chlorine–caustic soda, and nitric acid–nitrobenzene–aniline.

PRF resin.—Phenol-resorcinol-formaldehyde (PRF) resin is the primary resin used for both web-to-web joints and web-to-flange joints. PRF resins differ somewhat from the other resins in that hardeners are required to help in curing glue-laminated timbers and I-joists. The PRF LCI was retrieved from Wilson, which was based on eight plants surveyed in the United States that represented 63 percent of total production for the year 2005 (Wilson 2009).

MUF resin.—Melamine-urea-formaldehyde (MUF) resin production is essentially identical to the production of urea-formaldehyde resin (these resins are used for particleboard and medium-density fiberboards) with the exception that melamine, about 8 percent by weight on a neat resin basis, is substituted for a portion of the urea input. The inputs to produce 1 kg of neat MUF resin at 60 percent nonvolatile solids content consist of three primary chemicals on a dry basis of melamine at 0.081 kg, urea at 0.397 kg, and methanol at 0.304 kg; much lesser amounts of formic acid, ammonium sulfate, and sodium hydroxide; and 0.791 kg of water. MUF resin production data were retrieved from Wilson, based on the data collected from six plants in the United States that represented 77 percent of total production for the year 2005 (Wilson 2009). Based on CORRIM Phase I glue-laminated surveys, 0.96 kg of MUF resin was used to produce 1 m^3 of FJL (Puettmann and Wilson 2005; Puettmann et al. 2013a, 2013b). In this study, the MUF consumption value in the FJL manufacturing process was quantified as 1.235 kg/m^3 based on primary mill data. The resin was assumed to have a 65 percent solids content (Silva et al. 2015).

I-joist manufacturing.—Three main unit processes exist in I-joist manufacturing: routing and shaping of web and flanges, assembly of I-joists, and sawing and curing, with energy generation as an auxiliary process (US EPA 2002; Wilson and Dancer 2005a; Puettmann et al. 2013c, 2013d). Routing and shaping of web and flanges is the first step. This step requires machining of the OSB web pieces so that they fit together at the ends and tapering them on the top and bottom edges so that they can be fitted into the flanges. Flanges are made primarily from LVL along with some FJL. The flanges are routed their entire length to accept the inserted tapered OSB web material. Dry sawdust is generated as a coproduct. The resin application and pressing take place after the sizing of the I-joist web and flanges. Resin is applied in web-to-web and web-to-flange joints using MDI or PRF resin where assembly is done mechanically. I-joists are sawn to the desired size and allowed to cure. In some cases, the I-joist may be heated in a radio-frequency oven to accelerate resin cure time. For composite I-joist manufacturing details, see Wilson and Dancer (2004a, 2005a).

Inventory approach

The gate-to-gate LCI generated for US I-joist production was based on primary data collected from I-joist manufacturers for the year 2012. I-joist manufacturing LCI data from collected primary data sources were linked to available secondary LCI data. Data for the forestry operations and feedstocks (components) used in I-joist manufacturing, including OSB, FJL, and LVL, come from other CORRIM reports. For FJL LCI, softwood lumber manufacturing data developed by M. R. Milota (M. Puettmann, personal communication, April 24, 2015) were used as feedstock to produce the FJL. The data for OSB and LVL production were from LCI data developed from updating LVL and OSB manufacturing (Kaestner 2015; Bergman and Alanya-Rosenbaum 2017c, 2017d; Puettmann et al. 2016a, 2016b). In addition, forestry operations (Johnson et al. 2005; Puettmann et al. 2013c, 2013d) and finished I-joist packaging LCI data (Puettmann et al. 2013c, 2013d) were retrieved from the literature to construct the cradle-to-gate I-joist plant LCI. Secondary data, such as supply of electricity, natural gas, chemicals, transport, and disposal, were from peer-reviewed literature and the US LCI Database (National Renewable Energy Laboratory [NREL] 2012). Material and energy balances were performed from primary and secondary data to ensure data quality.

Cutoff rules

According to the PCR, if the mass–energy of a flow is less than 1 percent of the cumulative mass–energy of the model flow, it may be excluded, provided that its environmental relevance is minor. This analysis included all energy and mass flows for the primary data collected.

In the primary surveys, manufacturers were asked to report total hazardous air pollutants (HAPs) specific to their wood products manufacturing process regardless of whether they were less than the 1 percent cutoff. If applicable to the wood product, HAPs were reported later in the LCI Data section of Bergman and Alanya-Rosenbaum (2017a, 2017b) and thus are not excluded from this LCI. Under Title III of the Clean Air Act Amendments of 1990, the EPA has designated HAPs that wood products facilities are required to report as surrogates for all HAPs. These are methanol, acetaldehyde, formaldehyde, propionaldehyde (propanal), acrolein, and phenol. All HAPS were included in the LCI; no cutoff rules apply.

Data quality requirements

The present study collected primary data from representative I-joist manufacturers in the United States for two regions: the SE and the PNW. The primary mill data were collected through a survey questionnaire developed to address the production of I-joists. Then, with assistance from the APA, the surveys were mailed to I-joist manufacturing plants. The LCI data were generated based on the survey questionnaire filled out by I-joist manufacturing plants and follow-up calls to complement any missing data along with site visits. A total of two I-joist mills from seven manufacturing facilities completed the questionnaire in the SE region, while three of six provided data in the PNW region. The data represented the average technology of these regions. Total US I-joist production for 2012 was 109 thousand km (358,900 thousand ft) (APA 2014). Three US I-joist plants representing 30.7 percent of 2012 US production (33.6 thousand km [110,346,627 ft]) in the PNW region and two plants representing 27 percent of 2012 US production (29.5 thousand km [96,799,180 ft]) in the SE region participated in the study by providing primary data for the PNW and SE regions. The surveyed plants provided detailed annual production data on their facilities, including on-site energy consumption; transportation data; electricity and natural gas consumption; LVL, OSB, and FJL volumes; and I-joist production. The components of LVL and FJL to produce I-joists were produced in manufacturing facilities in the regions of the United States, while for OSB, US manufacturing of this material is only in the eastern United States. Most I-joist production occurs in conjunction with production of LVL and FJL in either the same engineered wood facility or nearby. For the surveyed mills in this study, all LVL production occurred at the same site as I-joist production and most FJL production as well.

To ensure data of the highest quality, data control measures were taken. Quantitative mass balances were performed to verify data quality. First, mass balances at individual facilities were conducted where the data were found to be consistent for the surveyed mills. Second, overall wood mass in and total wood mass out for both regions were calculated, and the difference was less than 2 percent. A difference less than 10 percent is considered good for wood product production. In addition, the primary data obtained from the surveys were analyzed using the weighted-average approach. The weighted coefficient of variation representing the variability in the collected process data was calculated and presented. Additionally, a sensitivity analysis investigating the energy inputs into I-joist production was performed to investigate the robustness of the impact assessment results.

Assumptions and limitations

The data collection, analysis, and assumptions followed the protocol defined by CORRIM in ''Research Guidelines for Life-Cycle Inventories'' (2014). To conform to ISO 14040 (ISO 2006b), additional considerations are listed below:

1. All flow analyses of wood and bark in the process were determined on an ovendry weight basis using a weighted-average green specific gravity of 0.55.
2. Although small in quantity relative to the wood mass, impacts from the production of the resin system were included in the analysis.
3. Because of the small consumption values for sodium hydroxide, catalyst, and melamine components of the resin system, no transportation data were provided or incorporated into the analysis.
4. Data collected from the participating facilities were analyzed using a weighted-average approach to develop a ''composite'' I-joist production facility. Where appropriate, missing data from facilities were not included in the weight averages. Inconsistent data were addressed by contacting facility personnel to solve the discrepancy.
5. The authors did not collect 2012 primary regional forest resource data but used secondary data from earlier LCA studies to develop the cradle-to-gate analysis. It is expected that forest resource data will be updated in the near future. As mentioned previously, to develop new EPDs, new underlying LCA data must be continually generated per the North American wood product PCR (FPInnovations 2015).
6. For regional forest harvesting, a single estimate of the average volume harvested per unit area was developed by weighting three combinations of management intensity (low, medium, and high intensity) and site productivity based on the relative percentage of the land base they occupy. Puettmann et al. (2013c, 2013d) list specific inputs, input assumptions, variations in harvest equipment, and fuel consumptions for the three management intensities for the two regions.
7. Harvesting cycles averaged 27 and 45 years for the SE and PNW, respectively.
8. Land use impacts, including biodiversity and biotic resource depletion, were not incorporated into the present study. The forests were considered to be replanted as forests and eventually returned to their previous state through forest management sustainability practices. Ecological impacts from harvesting forest resources are best covered by forest sustainable certification programs; thus, their impacts affecting plant and wildlife diversity, water quality, and other similar factors were not considered.
9. Forest carbon increases and decreases were not tracked, but the authors considered that the harvested trees were being sustainably managed through the ASTM standards D7612-10 and D7480-08 (ASTM International 2010, 2014b). Additionally, sustainably managed forests are virtually carbon neutral (Lippke et al. 2011).
10. Temporal dimensions of greenhouse gas (GHG) emissions were not included because the study focused on the cradle-to-gate production, which occurs within a relatively short time frame, versus cradle-to-grave production, where long-term GHG emissions and carbon sinks have a greater influence on the global warming (GW) impact category (Bergman 2012).
11. OSB was not manufactured in the PNW. The OSB manufacturing LCI data from Puettmann et al. (2016a; personal communication, April 24, 2015) were used for both the SE and PNW regions.
12. A mass balance was performed to verify data quality. A difference less than 10 percent was considered good for wood product manufacturing facilities.
13. Biogenic CO_2 emissions were tracked and reported, but the TRACI impact method does not count the contribution of wood-derived CO_2 emissions from burning wood fuel in the boiler toward the GW impact estimate (Bare 2011).
14. Carbon content for wood products is assumed to be 50 percent by mass of ovendried wood.
15. MUF resin was used as proxy for melamine-formaldehyde resin, which is used in the FJL production life-cycle stage.

Impact category method

The life-cycle impact assessment (LCIA) was performed using the TRACI 2 method (Bare 2011). Five impact categories were examined, including global warming potential (GWP [kg CO_2 eq]), acidification (kg SO_2 eq), eutrophication (kg N eq), ozone depletion (kg chlorofluorocarbons-11 eq), and photochemical smog (kg O_3 eq). The five impact categories evaluated in this study were in line with the requirement of the wood products PCR (FPInnovations 2015).

Sensitivity analysis

Sensitivity analysis is commonly used in the LCA to determine the effect of variations in assumptions, methods, and data on the results of the analysis. It allows identification of sensitive parameters that require high accuracy in order to improve the quality of the analysis. In this study, a sensitivity analysis was performed by investigating the impact of the variation of on-site energy consumption (i.e., natural gas and electricity) at the I-joist production life-cycle stage to the overall cradle-to-gate output. Sensitivity analysis was completed per ISO 14040 and 14044 standards (ISO 2006b, 2006c).

Results

LCI analysis

Table 1 provides the detailed data on the material inputs of the gate-to-gate I-joist production stage. Under materials, wood feedstocks included OSB, LVL, and FJL. The weighted production coefficient of variation (CoVw) values were calculated for system inputs and outputs to investigate data consistency where the product (I-joist) data showed high consistency between facilities, with a CoVw of 4.6 and 2.2 percent for the SE and PNW, respectively. The CoVw for total feedstock input was 7.5 percent (SE) and 4.7 percent (PNW).

The CoVw values of the I-joist manufacturing site energy inputs are presented in Table 2. Electricity and natural gas were the primary energy inputs in both regions, where both showed large variation. Although the input wood raw material has a high energy potential, the feedstock energy of the wood raw material was not included as an energy input because this wood was not used as an energy source in the system investigated. The feedstock energy in the wood leaves the system still embodied in the product and coproducts, as shown in Table 1.

Air emissions were derived from the data received from the surveyed mills along with pertinent emissions data categorized by the USEPA (2002). Most of the air emission data were the on-site air emissions reported by the surveyed I-joist manufacturers, while the acetone emissions were augmented by a secondary data source (Table 3; US EPA 2002). The main emission sources were from hot presses. Baghouses were the primary collectors of particulate matter (PM), with all surveyed plants using the emission control device (ECD; US EPA 2003a). To reduce volatile organic compound (VOC) emissions from dryers, plants reported the use of regenerative thermal oxidizers (RCOs), sometimes referred to as regenerative thermal oxidizers (RTOs), and wet scrubbers (US EPA 2003b). Thermal oxidizers are typically fueled by natural gas. RCOs are designed to destroy VOCs and other emissions, including PM and soot (US EPA 2003c).

Table 1.—Gate-to-gate material flow analysis of 1 km of I-joist manufacturing in the Southeast (SE) and Pacific Northwest (PNW) regions.

		Values	
	Unit	SE	PNW
Products[a]			
I-joist	km	1.00	1.00
Sawdust, sold	kg	411	363
Sawdust, wood fuel	kg	0.69	0.00
Panel trim, sold	kg	17.13	2.21
Rejects	kg	0.00	9.87
Resources			
Water, well, in ground		0.32	4.63
Materials			
Wood feedstock, LVL, oven-dried	kg	2,597	2,318
Wood feedstock, OSB, oven-dried	kg	2,212	1,583
Wood feedstock, FJL, oven-dried	kg	28.26	847.33
Phenol-resorcinol-formaldehyde resin	kg	33.52	15.68
MDI (proxy for emulsion polymer isocyanate)	kg	1.47	0.00
Polyurethane polymer	kg	0.31	0.00
Hardener		0.55	8.97
Catalyst		0.00	1.96
Ancillary material			
Hydraulic fluid	kg	0.026	0.107
Greases	kg	0.006	0.003
Motor oil	kg	0.026	0.043
Waxes (sealant)	kg	0.000	0.036

[a] Ovendry basis.

Based on mill surveys, the weighted-average one-way haul distance for feedstock along with the components of the resin system are provided in Table 4. The zero values for LVL shipping distances in the PNW represent the LVL produced concurrently at the I-joist production site. All upstream transportation of inputs to LVL, FJL, and OSB production were included in the respective LCI input values.

Cumulative energy consumption

The cumulative primary energy consumption (CPEC) for the cradle-to-gate production of SE and PNW I-joists is provided in Tables 5 and 6, respectively. The LVL stage was responsible for the majority of the primary energy consumption with 55 and 51 percent for the SE and PNW, respectively. This was due to high natural gas and wood fuel consumption, where the wood and natural gas were used to generate thermal energy for log conditioning and for drying and pressing veneers at the LVL stage.

Total energy use at the I-joist production stage was dominated by fossil fuels, where the greatest contributor was natural gas followed by coal and crude oil. At the I-joist life-cycle production stage, natural gas was used to generate thermal energy for resin curing and emission control (e.g., thermal oxidizers), and electricity was consumed for sawing, trimming, resin curing (e.g., the radio-frequency ovens), and emission control (e.g., RCOs).

Table 2.—Gate-to-gate weighted-average on-site energy inputs to produce 1 km of I-joist.

	Southeast			Pacific Northwest		
Energy inputs	Quantity	Unit	CoVw (%)[a]	Quantity	Unit	CoVw (%)
Electricity	258	kWh	33	378	kWh	35
Natural gas	41	m^3	49	36.4	m^3	103
Diesel	4.77	liters	16	2.99	liters	76
Propane	4.74	liters	5.3	3.87	liters	4.7
Gasoline	0.217	liters	141	0.054	liters	—

[a] CoVw = production-weighted coefficient of variation.

Life-cycle impact assessment

In this study, five midpoint impact categories were investigated. Environmental performance results for five impact categories along with energy consumption from nonrenewable fossil and nuclear fuels, renewables (wind, hydroelectric, solar, geothermal), renewable and nonrenewable resource use, and solid waste generated are presented in Tables 7 and 8 for the SE and PNW, regions, respectively. Overall cradle-to-gate primary energy consumption was 82.0 and 74.2 GJ/km for all five life-cycle stages in the SE and PNW, respectively. Solid waste generated through the life cycle was dominated by the LVL stage followed by I-joist and OSB production stages. Solid emissions include ash generated at the wood boiler during veneer production for LVL production, and primarily fuels and resins used.

In addition, the contribution of life-cycle stages to the overall impact for eutrophication, acidification, smog, and GW impact categories are provided in Figure 2. The GW impact category was dominated by LVL production, followed by OSB and I-joist manufacturing stages; the major contributors at the I-joist stage production were electricity use in both regions (37% and 35% in SE and PNW, respectively), followed by natural gas use (21%) in the SE and transportation (34%) in the PNW. The contribution of the LVL production stage to GW was about 42 and 55 percent for the SE and PNW, respectively. The I-joist production stage had a notable contribution at two impact categories investigated owing to PRF resin consumption: ozone depletion and eutrophication. Forest operations had a minor contribution to the overall impact in both regions.

Table 3.—Direct outputs reported from production of 1 km of I-joist, gate to gate.[a]

	Unit	Southeast	Pacific Northwest
Emissions to air			
Acetone	kg	0.0002	0.0002
Acrolein	kg	bdl	bdl
Carbon monoxide	kg	0.0552	0.0297
Formaldehyde	kg	0.0046	0.0130
Methanol	kg	0.0398	0.0309
Nitrous oxide	kg	0.0671	0.0351
$PM_{2.5}$[b]	kg	0.1027	0.0000
PM_{10}	kg	0.1027	0.0043
Phenol	kg	0.0943	0.3521
Propionaldehyde	kg	bdl	bdl
Sulfur dioxide	kg	0.0007	0.0003
VOC	kg	0.3694	0.1819
Solid waste			
Waste to inert landfill	kg	0.00	3.73
Waste to recycling	kg	6.38	2.45

[a] bdl = below detection limit; PM = particulate matter, 2.5 and 10 μm; VOC = volatile organic compounds.

Scenario analysis

In this study, both mass and economic allocations were performed to investigate the influence of the allocation method on the resulting impact. The contribution of five life-cycle stages to the LCA results for mass and economic allocation are provided in Tables 9 and 10 for the SE and PNW, respectively. Applying economic allocation resulted in increased impact of the I-joist production stage compared with mass allocation because of the low value of the coproducts generated at this stage. Overall, the change in contribution of different life-cycle stages to various impact categories was minor when economic allocation was used.

Comparison

The on-site, industry-average energy consumption at the I-joist production plant was compared with a previous CORRIM Phase I study that developed LCI for US I-joist production based on 2000 data (Wilson and Dancer 2005a; Puettmann et al. 2013c, 2013d). In particular, the natural gas consumption reported in 2012 was substantially higher compared with the Phase I study in both regions (Tables 11 and 12). In addition, diesel consumption in the SE and PNW and propane consumption in the PNW, which were relatively small inputs, showed a high variation. In particular for the SE, natural gas consumption drove the total impact from energy with a change of 587 percent (Table 11). As expected from the higher CPEC value found

Table 4.—Weighted-average delivery distance (one-way) by mode for materials to I-joist plant.[a]

	Delivery distance (km)	
	Southeast	Pacific Northwest
OSB to I-joist plant, by truck	175	1,604
OSB to I-joist plant, by rail	0	333
LVL to I-joist plant	112	0
Finger-jointed lumber to I-joist plant	230	40
MDI and PRF resin to I-joist plant	89	161

[a] OSB = oriented strandboard; LVL = laminated veneer lumber; MDI =← methylene diphenyl diisocyanate; PRF = phenol-resorcinol-formaldehyde.

Table 5.—Cumulative primary energy consumption per 1 km of cradle-to-gate I-joist in the Southeast region (mass allocation).[a]

Fuel	Southeast					
	%	Forestry operations	OSB production	FJL production	LVL production	I-joist production
Renewable fuel use						
Wood fuel	35.0	0.00E+00	1.16E+04	2.08E+02	1.67E+04	1.92E+02
Nonrenewable fuel use						
Natural gas	27.7	3.97E+02	5.58E+03	1.10E+01	1.28E+04	3.88E+03
Coal	18.1	5.77E+01	4.03E+03	3.01E+01	8.33E+03	2.41E+03
Crude oil	11.7	1.56E+03	2.00E+03	1.36E+01	3.73E+03	2.30E+03
Uranium	7.3	1.94E+01	1.66E+03	1.23E+01	3.42E+03	8.44E+02
Renewable energy sources						
Hydropower	0.2	2.35E 01	3.21E+01	2.31E 01	7.74E+01	1.92E+01
Other	0.0	0.00E+00	7.24E 01	3.42E 04	8.80E 01	2.60E+00
Total	100	2.04E+03	2.50E+04	2.75E+02	4.51E+04	9.64E+03
Total (%)		2.5	30.4	0.3	55.0	11.8

[a] OSB = oriented strandboard; FJL = finger-jointed lumber; LVL = laminated veneer lumber.

Table 6.—Cumulative primary energy consumption per 1 km of cradle-to-gate I-joist in the Pacific Northwest region (mass allocation).[a]

Fuel	Pacific Northwest					
	%	Forestry operations	OSB production	FJL production	LVL production	I-joist production
Renewable fuel use						
Wood fuel	44.6	0.00E+00	8.33E+03	4.46E+03	2.01E+04	1.94E+02
Nonrenewable fuel use						
Natural gas	23.4	9.58E+01	3.99E+03	6.28E+02	8.08E+03	4.58E+03
Coal	13.2	5.16E+01	2.89E+03	4.00E+02	4.51E+03	1.95E+03
Crude oil	12.8	1.55E+03	1.43E+03	3.85E+02	2.85E+03	3.29E+03
Uranium	4.3	1.77E+01	1.19E+03	1.27E+02	1.35E+03	4.99E+02
Renewable energy sources						
Hydropower	1.4	1.81E 01	2.29E+01	7.35E+00	6.96E+02	2.80E+02
Other	0.3	0.00E+00	5.18E 01	3.40E 03	1.43E+02	5.86E+01
Total	100	1.71E+03	1.79E+04	6.00E+03	3.77E+04	1.09E+04
Total (%)		2.3	24.1	8.1	50.9	14.6

[a] OSB = oriented strandboard; FJL = finger-jointed lumber; LVL = laminated veneer lumber.

Table 7.—Environmental performance of 1 km of I-joist, cradle to gate, Southeast region (mass allocation).[a]

Impact category	Unit	Total	Forestry operations	OSB production	FJL production	LVL production	I-joist production
Impact category							
Global warming	kg CO_2 eq	2.72E+03	1.29E+02	6.36E+02	3.82E+00	1.49E+03	4.57E+02
Acidification	kg SO_2 eq	2.66E+01	1.72E+00	6.26E+00	4.03E 02	1.40E+01	4.50E+00
Eutrophication	kg N eq	1.22E+00	3.14E 01	1.64E 01	1.20E 03	3.65E 01	3.78E 01
Ozone depletion	kg CFC-11 eq	1.78E 04	1.10E 08	2.21E 06	3.66E 09	7.71E 07	1.75E 04
Smog	kg O_3 eq	2.91E+02	4.87E+01	6.40E+01	8.00E 01	1.36E+02	4.14E+01
Total primary energy consumption	MJ	8.20E+04	2.04E+03	2.50E+04	2.75E+02	4.51E+04	9.64E+03
Nonrenewable fossil	MJ	4.72E+04	2.02E+03	1.16E+04	5.46E+01	2.49E+04	8.58E+03
Nonrenewable nuclear	MJ	5.96E+03	1.94E+01	1.66E+03	1.23E+01	3.42E+03	8.44E+02
Renewable (solar, wind, hydroelectric, and geothermal)	MJ	1.33E+02	2.35E 01	3.28E+01	2.31E 01	7.82E+01	2.18E+01
Renewable, biomass	MJ	2.87E+04	0.00E+00	1.16E+04	2.08E+02	1.67E+04	1.92E+02
Material resources consumption (nonfuel resources)							
Nonrenewable materials	kg	1.49E+01	0.00E+00	6.18E+00	1.06E 03	8.08E+00	6.16E 01
Renewable materials	kg	4.07E+03	7.17E+02	2.07E+01	3.62E+01	327E+03	1.99E+01
Freshwater	liters	1.22E+04	4.22E 01	1.40E+03	3.23E+01	6.12E+03	4.61E+03
Waste generated							
Solid waste	kg	1.07E+02	0.00E+00	1.17E+01	1.89E 04	8.89E+01	6.85E+00

[a] OSB = oriented strandboard; FJL = finger-jointed lumber; LVL = laminated veneer lumber; CFC = chlorofluorocarbons.

Table 8.—Environmental performance of 1 km of I-joist, cradle to gate, Pacific Northwest region (mass allocation).[a]

	Unit	Total	Forestry operations	OSB production	FJL production	LVL production	I-joist production
Impact category							
Global warming	kg CO_2 eq	2.10E+03	1.13E+02	4.55E+02	9.06E+01	8.83E+02	5.57E+02
Acidification	kg SO_2 eq	2.082E+01	1.54E+00	4.48E+00	9.77E 01	9.12E+00	4.71E+00
Eutrophication	kg N eq	7.91E 01	1.05E 01	1.17E 01	3.23E 02	2.85E 01	2.51E+01
Ozone depletion	kg CFC-11 eq	8.65E 05	5.08E 09	1.58E 06	1.15E 07	2.03E 06	8.28E 05
Smog	kg O_3 eq	2.77E+02	4.84E+01	4.58E+01	1.69E+01	1.13E+02	5.27E+01
Total primary energy consumption	MJ	7.42E+04	1.71E+03	1.79E+04	6.00E+03	3.77E+04	1.09E+04
Nonrenewable fossil	MJ	3.67E+04	1.69E+03	8.31E+03	1.41E+03	1.54E+04	9.83E+03
Nonrenewable nuclear	MJ	3.18E+03	1.77E+01	1.19E+03	1.27E+02	1.35E+03	4.99E+02
Renewable (solar, wind, hydroelectric, and geothermal)	MJ	1.21E+03	1.81E 01	2.35E+01	7.35E+00	8.38E+02	3.39E+02
Renewable, biomass	MJ	3.31E+04	0.00E+00	8.33E+03	4.46E+03	2.01E+04	1.94E+02
Material resources consumption (nonfuel resources)							
Nonrenewable materials	kg	2.70E+01	0.00E+00	4.42E+00	2.24E 02	2.19E+01	6.22E 01
Renewable materials	kg	3.92E+03	0.00E+00	1.37E+01	8.70E+02	3.01E+03	2.00E+01
Freshwater	liters	8.99E+03	9.83E+01	1.00E+03	8.09E+02	5.17E+03	1.90E+03
Waste generated							
Solid waste	kg	5.42E+01	0.00E+00	8.40E+00	2.62E 01	3.91E+01	6.73E+00

[a] OSB = oriented strandboard; FJL = finger-jointed lumber; LVL = laminated veneer lumber; CFC = chlorofluorocarbons.

earlier, the on-site energy inputs were substantially higher than for Phase I for the PNW as well (Wilson and Dancer 2005a; Puettmann et al. 2013c, 2013d). As for the PNW, electricity, along with natural gas consumption, drove the total impact from energy with changes of 37 and 7,820 percent, respectively (Table 12). Therefore, a sensitivity analysis was conducted to investigate the energy inputs into I-joist production to see their overall impact. However, the apparent statistical differences between the older and current studies could not be adequately addressed because

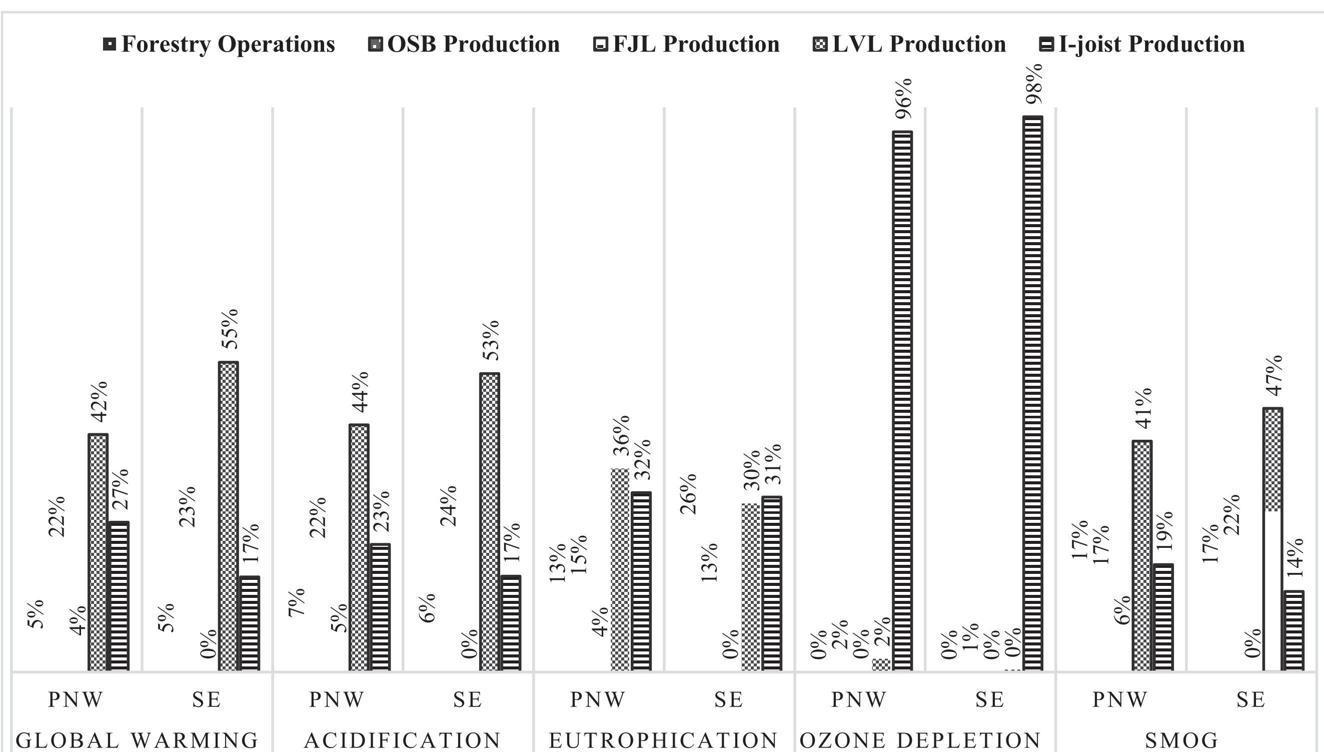

Figure 2.—Contribution of the life-cycle stages of I-joist production to the resulting environmental impact in the Pacific Northwest (PNW) and Southeast (SE) regions of the United States (mass allocation). OSB = oriented strandboard; FJL = finger-jointed lumber; LVL = laminated veneer lumber.

Table 9.—Environmental impact assessment results for mass and economic allocation for the Southeast region.[a]

Impact category	Unit	Forestry operations (%)	OSB production (%)	FJL production (%)	LVL production (%)	I-joist production (%)
Mass allocation						
Global warming	kg CO_2 eq	4.7	23.4	0.1	54.9	16.8
Acidification	kg SO_2 eq	6.5	23.6	0.2	52.9	17.0
Eutrophication	kg N eq	25.7	13.4	0.1	29.9	31.0
Ozone depletion	kg CFC-11 eq	0.0	1.2	0.0	0.4	98.3
Smog	kg O_3 eq	16.8	22.0	0.3	46.7	14.3
Economic allocation						
Global warming	kg CO_2 eq	4.5	24.2	0.2	53.5	17.6
Acidification	kg SO_2 eq	6.2	24.4	0.2	51.5	17.8
Eutrophication	kg N eq	24.5	13.8	0.1	29.1	32.4
Ozone depletion	kg CFC-11 eq	0.0	1.2	0.0	0.4	98.3
Smog	kg O_3 eq	16.2	23.0	0.4	45.3	15.1

[a] OSB = oriented strandboard; FJL = finger-jointed lumber; LVL = laminated veneer lumber; CFC = chlorofluorocarbons.

Table 10.—Environmental impact assessment results for mass and economic allocation for the Pacific Northwest region.[a]

Impact category	Unit	Forestry operations (%)	OSB production (%)	FJL production (%)	LVL production (%)	I-joist production (%)
Mass allocation						
Global warming	kg CO_2 eq	5.4	21.7	4.3	42.1	36.5
Acidification	kg SO_2 eq	7.4	21.5	4.7	43.8	22.6
Eutrophication	kg N eq	13.3	14.8	4.1	36.0	31.8
Ozone depletion	kg CFC-11 eq	0.0	1.8	0.1	2.3	95.7
Smog	kg O_3 eq	17.5	16.5	6.1	40.9	19.0
Economic allocation						
Global warming	kg CO_2 eq	5.0	21.8	6.5	39.8	26.8
Acidification	kg SO_2 eq	6.9	21.8	6.8	41.4	23.0
Eutrophication	kg N eq	12.5	15.0	6.0	34.1	32.4
Ozone depletion	kg CFC-11 eq	0.0	1.8	0.2	2.4	95.6
Smog	kg O_3 eq	16.5	16.9	9.0	38.2	19.5

[a] OSB = oriented strandboard; FJL = finger-jointed lumber; LVL = laminated veneer lumber; CFC = chlorofluorocarbons.

no statistical description of the data from the earlier study was available. The earlier CORRIM study did not perform sensitivity analysis. However, there was sufficient reason to attempt to quantify the energy impacts associated with I-joist production.

The CO_2 emissions released during the forest operations; the manufacturing of the three components OSB, FJL, and LV-L; and the final product, I-joist, and carbon stored in the product are provided in Table 13 minus the weight of the resin. Based on carbon stage calculation, 1 km of I-joist stores 7,285 and 7,255 kg CO_2 eq[1] for the SE and PNW, respectively, where the carbon storage in the final product was about three times more than the carbon emissions that occurred during its production. This result supported the amount of carbon emission savings showed by Bergman and et al. (2014) when replacing a steel I-joist with a comparable composite wood I-joist along with the importance of carbon being stored in wood (Lippke et al. 2010).

[1] 4,415 ovendried (OD) kg of wood in I-joist × 0.9 × (0.5 kg carbon/1.0 OD kg wood) × (44 kg CO_2/kmole/12 kg carbon/kmole) =← 7,285 kg CO_2 eq. 4,397 OD kg of wood in I-joist × 0.9 × (0.5 kg carbon/1.0 OD kg wood) × (44 kg CO_2/kmole/12 kg carbon/kmole) = 7,255 kg CO_2 eq.

Table 11.—Production weighted-average Southeast region on-site energy inputs for manufacturing 1 km of I-joist.

Energy inputs	Quantity: Southeast Phase I	Quantity: Southeast 2012	Unit	% change
Electricity	246	257.8	kWh	5
Natural gas	5.95	40.9	m^3	587
Diesel	3.6	4.77	liters	33
Propane	4.72	4.74	liters	0

Table 12.—Production weighted-average Pacific Northwest region on-site energy inputs for manufacturing 1 km of I-joist.

Energy inputs	Quantity: Pacific Northwest Phase I	Quantity: Pacific Northwest 2012	Unit	% change
Electricity	276	377.8	kWh	37
Natural gas	0.46	36.42	m^3	7,820
Diesel	0.99	2.99	liters	202
Propane	2.04	3.87	liters	90

Table 13.—*Carbon balance per kilometer of I-joist.*

Carbon source	kg CO_2 equivalent	
	Southeast	Pacific Northwest
Released forestry operations	129	113
Released manufacturing	2,588	1,986
CO_2 eq stored in product	7,285	7,255

Sensitivity analysis

A sensitivity analysis was performed in accordance with the ISO 14040 standard to model the cradle-to-gate effects of varying on-site natural gas consumption and electricity consumption during I-joist production. Neither natural gas nor electrical consumption on-site had a substantial impact on the overall process because on-site I-joist production CPEC contributed only roughly 13 and 16 percent of the energy impacts of cradle-to-gate I-joist production in the SE and PNW, respectively.

Conclusions

This study presented the updated cradle-to-grave LCI and LCIA data for composite I-joist manufacturing in the United States. The cradle-to-gate LCA for I-joist includes the LCI of (1) forest resources, (2) OSB production, (3) FJL production, (4) LVL production, and (5) I-joist production. The data generated relied on primary data collected in 2012 from manufacturers in the US SE and PNW regions that were complemented with secondary data from peer-reviewed literature and databases. The data were representative of the I-joist sizes and production volumes consistent with trade association production data in the United States.

The amount and type of energy consumed in the production process are major concerns and are typically associated with the environmental performance of a product or a service. The results of the study indicated that the primary energy consumption at the I-joist life-cycle stage does not have a major contribution to overall CPEC, where the major contributor was the LVL production stage for both regions followed by OSB production. The LVL stage, which included the dry veneer stage, had a substantial role in the overall energy consumption with a 55 and 51 percent contribution to the total primary energy consumption in the SE and PNW regions, respectively. As shown by Bergman and Alanya-Rosenbaum (2017c, 2017d, 2017e), dry veneer production consumed the most energy within LVL production. Energy consumption at I-joist life-cycle stage was dependent mainly on fossil fuels. Additionally, the energy source used in generating the electricity in these regions had an important role on this because both electricity grids are fossil fuel dominant. The results obtained from LCA analysis revealed that the PRF resin consumption at I-joist production was also responsible for high contribution of this stage in ozone depletion and eutrophication in the SE and PNW. For both regions, high fuel consumption resulting from thermal energy required at the LVL stage was the main reason for its high contribution to the GW impact category. At the I-joist production stage, for the SE region, PRF resin use and electricity together constitute about 55 percent, and in the PNW region, electricity consumption along with transportation constitute about 69 percent of the overall GW, respectively. On the other hand, life-cycle energy consumption and emissions from the forest resources were minor relative to other manufacturing life-cycle stages (LVL, OSB, FJL, and I-joist).

Increased energy consumption for some wood products has increased over the years although not necessarily from production itself but from auxiliary activities, such as emission control. In this study, cradle-to-gate CPEC of I-joist production for the United States was substantially higher compared with earlier CORRIM studies. Yet the authors can only speculate on the obvious differences because of the lack of statistical analysis of the data from other, earlier studies. Anyway, the scenario analysis conducted indicated that I-joist production itself was a minor contributor to the overall process in terms of energy inputs. As for energy inputs for I-joist production itself, one possible reason is the greater use of ECDs, such as RCOs (or thermal oxidizers), becoming more widespread because of increased regulatory controls in the United States since the 2000s, when the original survey data were collected. Because thermal oxidizers are now more widely used in manufacturing of wood products to help destroy VOC emissions, it would have a substantial effect on the results in other wood product systems as well because they are typically fueled by natural gas. In support of this conclusion, the updated OSB study by Puettmann et al. (2016a) also reported increased use of RTOs, which could cause high natural gas consumption outside of energy consumed for production itself. The PNW plywood study also reported installation of RTOs and electrostatic precipitators at the surveyed mills between 2000 and 2012 (Puettmann et al. 2016b). This is also consistent with LVL production (Bergman and Alanya-Rosenbaum 2017c, 2017d, 2017e). Therefore, the resultant higher CPEC values for 2012 than for 2000 can be considered as an environmental trade-off to reduce emissions such as VOCs (or HAPs).

Recommendations are made for future work on LCIA of I-joist manufacturing in the United States. First, expand the system boundaries by including the use and disposal phases of the I-joist product. The cradle-to-grave analysis will allow for a more comprehensive assessment of hot spots in the whole product life cycle, including evaluating the potential for cascade use of I-joists at end of life for either further material utilization or energy production (Höglmeier et al. 2015). Second, upload the I-joist production LCI data into a publicly available LCI database, such as the Federal LCA Commons (US Department of Agriculture, Agriculture Research Service, National Agricultural Library 2010) or the US LCI Database (NREL 2012).

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