LIFE CYCLE INVENTORY OF MANUFACTURING PREFINISHED ENGINEERED WOOD FLOORING IN EASTERN US WITH COMPARSION TO SOLID STRIP WOOD FLOORING

*Richard D. Bergman**†

Graduate Research Assistant
E-mail: rbergman@fs.fed.us

Scott A. Bowe†

Associate Professor
Department of Forest and Wildlife Ecology
University of Wisconsin
Madison, WI 53705-1598
E-mail: sbowe@wisc.edu

(Received December 2010)

Abstract. Building products have come under increased scrutiny because of environmental impacts from their manufacture. Our study followed the life cycle inventory approach for prefinished engineered wood flooring in the eastern US and compared the results with those of solid strip wood flooring. Our study surveyed five engineered wood flooring manufacturers in the eastern US. These production facilities represented 18.7% of total annual production in 2007. Primary data collected for 2007 included annual production, energy consumption and type, material inputs, emission data, product outputs, and other coproducts. Modeling data estimated biogenic and fossil CO_2 emissions at 623 and 1050 kg/m^3, respectively, and volatile organic compounds at 1.04 kg/m^3. Cumulative allocated energy consumption for prefinished engineered wood flooring was 23.0 GJ/m^3 with 40% coming from coal. Unfinished solid strip flooring cumulative energy consumption was only 6.50 GJ/m^3 with 65% from biomass, roughly half that of unfinished engineered wood flooring. However, after converting to an area (in-use) basis, unfinished engineered wood flooring consumed 136 MJ/m^2 compared with 123 MJ/m^2 for unfinished solid strip flooring. After changing to an in-use parameter, the two wood flooring products were similar in energy consumption during manufacturing, but engineered wood flooring still consumed significantly more fossil fuel.

Keywords: Life cycle inventory, prefinished engineered wood, wood flooring, environmental impact, carbon.

INTRODUCTION

Components of residential or commercial buildings are evaluated because of concerns about their environmental impact, especially in relation to climate change. Some research claims that the main cause of climate change is fossil fuel burning (IPCC 2007). Therefore, carbon emissions are playing an increasingly important role in policy decision-making in the US and throughout the world. Some building products consume large amounts of fossil fuels during processing (Khatib 2009). However, wood building products typically consume more biomass than fossil fuels during manufacturing, a significant environmental advantage (Puettmann and Wilson 2005). Biomass carbon dioxide (CO_2) accumulates less in the atmosphere because biomass is rapidly recoverable by plant growth and carbon is fixed in the final product (EPA 2003; UNFCCC 2003; Lippke et al 2010).

The practice of improving construction, operation, and energy efficiency of buildings while decreasing overall environmental impact is called green building. The US market for green building materials is expected to increase from

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* Corresponding author
† SWST member

Wood and Fiber Science, 43(4), 2011, pp. 421-441

an estimated \$9.6 billion in 2009 to nearly \$31.4 billion in 2014, for a 5-yr compound annual growth rate of 26.7%. The value of interior materials such as flooring is predicted to increase from \$2 billion in 2009 to \$5.8 billion in 2014 (McWilliams 2010). Having a sound green building policy for building practices in the US would significantly decrease the environmental impact on the world's resources. However, to evaluate building materials and practices regarding their environmental impact for creating such a policy and addressing environmental claims, life cycle information is necessary.

Conducting a life cycle inventory (LCI) for products is part of a science-based approach to addressing environmental claims. LCI data are a major part of life cycle assessments (LCA). LCA use rigorous methodology to find the total environmental profile for a particular product referred to as cradle-to-grave (raw material extraction to waste disposal) analysis. These analyses include environmental and energy costs on a per-unit basis using data from individual LCI studies. LCI studies include resource extraction, raw material and product transportation, primary and secondary processing, final product use, maintenance, and final disposal. For the manufacturing stage, LCI measures all raw material and energy inputs and outputs including emissions to manufacture a particular product on a per-unit basis within carefully defined system boundaries, eg a gate-to-gate LCI. The LCI results are used to assess environmental impact (ISO 2006b, 2006c). In the US, the Consortium for Research on Renewable Industrial Materials (CORRIM) has developed many LCI data sets for wood materials (NREL 2004).

CORRIM has examined wood as a suitable environmental choice by developing LCI data of wood materials using the standardized tools of LCI analysis. CORRIM is helping build a multinational database of environmental and economic impacts associated with using renewable materials (Bowyer et al 2001). This LCI study for prefinished engineered wood flooring uses methodology and protocols put forth by CORRIM and the International Organization of Standardization (ISO) (ISO 2006b, 2006c; CORRIM 2010). Results from this project may aid LCA practitioners conducting studies that document use of wood products in building construction for their entire life cycle (cradle-to-grave).

REVIEW OF RELEVANT LCI STUDIES

Previous Studies

Previous studies on flooring products included both the US and Europe. Hubbard and Bowe (2008) evaluated unfinished solid wood flooring in the eastern US. About 86% of the total energy (including electricity) needed for making the flooring came from biomass (wood residue). This result is consistent with other LCI studies on wood products that show a high percentage of process energy coming from biomass (Puettmann and Wilson 2005). Also, Gustavsson et al (2010) found that substituting biomass residue from wood products for fossil fuels significantly lowered net CO_2 emissions. Petersen and Solberg (2005) reviewed 14 LCA studies from Norway and Sweden, whereas Werner and Richter (2007) reviewed international research from the past 20 yr. The main conclusion is that wood tends to have a favorable environmental profile particularly regarding greenhouse gas emissions (GHGs) compared with competing materials such as steel and concrete.

In Sweden, Jönsson et al (1997) reported that solid wood flooring showed significant environmental advantages compared with linoleum and vinyl flooring. Vinyl flooring had the greatest environmental impact. Raw materials play a significant role in environmental impact for each product because the final product with the greatest impact tended to be the product using synthetics derived from fossil fuels. For example, polyvinyl chloride used in vinyl flooring production is synthesized from ethylene made from crude oil. Another reason for the greater impact associated with vinyl flooring was that its production consumed the most nonrenewable energy resources. Wood flooring used the least nonrenewable energy resources, and its main raw component was trees, a renewable resource.

A 2006 German study provided data on environmental impacts of types of prefinished wood flooring including solid wood, solid and multilayer parquets, and wood blocks (Nebel et al 2006). Nebel et al (2006) found that solvent use and energy consumption had the most effect on environmental performance of these products. This life cycle study provided results from extraction of raw material to final disposal of material. One important factor was the expected lifetime of a given product and its ability to be refurbished. Wood blocks, wood floor boards, and 22-mm parquet flooring had an expected useful life of 50 yr, which was at least twice the useful life of other wood flooring products such as multilayer parquet flooring. Wood block flooring is made from tongue and groove wood blocks that are 19-38 mm thick, up to 90 mm wide, and 150-380 mm long. In this study, wood block flooring was 38 mm thick, nearly twice as thick as the wood floor boards. In addition, the 50 yr corresponded to the expected useful life of the house. An environmental advantage was the air drying of wood floor boards to 17% MC that decreased primary energy consumption to 25% of multilayer parquet. The reference flow was 1 m^2 of laid flooring for 50 yr. Multilayer parquet had only an expected useful life of 10 yr. As other studies have shown, energy consumption during manufacturing was the highest of the individual life cycle stages. In addition, burning the disposed material for energy lowered the flooring's impact at end of life. Solvents used in lay up, prefinishing, and refurbishing played the largest role in photo-oxidant formation, caused mainly by emissions of volatile organic compounds (VOCs).

Coatings play a large role in some wood products, and the coating with the lowest environmental impact is not always obvious. Gustafsson and Börjesson (2007) found through a cradle-to-grave evaluation that a "green" wax produced from rapeseed oil had a greater overall environmental impact than the two ultraviolet (UV) light hardening lacquers, whereas the 100% UV lacquer showed the least environmental impact. In addition, Tufvesson and Börjesson (2008) found that wax ester made from rapeseed oil had about 3.5 times higher global warming potential than paraffin wax. Furthermore, cultivation of rapeseed oil causes soil emissions of ammonia and nitrous oxides, resulting in potential acidification and eutrophication. These results indicate that more work is needed to find coatings with minimal environmental impact.

Lessons Learned

The initial work of CORRIM examined structural wood building products used in residential home construction (Lippke et al 2004; Perez-Garcia et al 2005; Puettmann and Wilson 2005). In each of these studies, wood building materials were found to have smaller environmental impacts than competing nonwood materials such as steel and concrete. Current CORRIM efforts are focusing on nonstructural building products such as interior finish materials. Wood products tend to have lower environmental impact than competing wood products because biomass, considered carbon-neutral, is used as a primary energy source in their production.

The useful life of a product plays a large role in its environmental impact. Some flooring products need to be replaced multiple times during the life of a house, whereas others are more durable. Some products are able to be refurbished more easily than others, and refurbishing flooring instead of replacing it decreases its overall environmental impact (Nebel et al 2006).

Caution is needed when addressing coatings to ensure that the whole life cycle of the material is evaluated for its environmental burdens. A "green" coating does not necessarily have less environmental impact than a competing product. A product must be examined from the raw material stage to its final disposal (ie cradle-to-grave

LCA) to provide the most accurate evaluation of environmental impact.

INDUSTRY OVERVIEW

Prefinished engineered wood flooring is a nonstructural wood product. Prefinished engineered wood flooring is more dimensionally stable than solid strip wood flooring because it is made up of cross-laminated veneers; this arrangement decreases shrinking and swelling in width that result from changes in moisture content. Engineered wood flooring as defined by the National Wood Flooring Association (NWFA) comprises several sheets of solid wood (veneer) bonded together with an adhesive under heat, pressure, or both. Although plies with two, three, five, seven, or nine sheets are available, three and five are most common. Prefinished engineered wood flooring is one of many commercially available flooring products. Competing products include solid strip wood, laminated wood, carpet, vinyl, ceramic tile, and laminated bamboo flooring.

In 2007, wood flooring manufacturers in the US produced 41.67 million m^2 solid wood and 36.36 million m^2 engineered wood flooring for a total of 78.03 million m^2 (CRI 2008). Market percentage of engineered wood flooring out of the total wood flooring market increased from 42.1% in 2004 to 46.6% in 2007 (CRI 2008). This increase in market share occurred although its production had actually decreased because of the severe decline in domestic housing construction (USDC 2011). However, hard surface flooring demand is expected to increase 2.8% annually from 2008 to 710 million m^2 by 2013, and the wood flooring market share is expected to increase, whereas vinyl flooring continues to lose market share. As before the recession, the remodeling market will be the driving force for hard surface flooring consumption because new residential construction consumes only 20% (Freedonia 2009a). In addition, the market for wood coatings has also declined because of the downturn in the US housing market, although is it also expected to rebound. An increase in wood flooring production results in an increase in wood coatings (protection) production. Total value of the wood protection and preservative market is forecast to be $3.3 billion by 2013. Although this value does include the treated wood market, the greatest increase in demand is expected to occur in interior wood applications such as flooring. The release of VOCs, including formaldehyde, during prefinishing and refurbishing will be an issue that is likely to affect market share. Coatings with an improved formulation that show better environmental performance are expected to gather a higher market share (Freedonia 2009b).

GOAL OF THE STUDY

The goal of this study was to document the LCI of prefinished engineered wood flooring production from incoming hardwood logs to prefinished engineered wood flooring in the eastern US (Fig 1). Our study showed material flow, energy consumption, air pollution, water effluent, and solid waste for the prefinished engineered wood flooring manufacturing process on a per-unit basis. We collected primary data by surveying veneer mills and flooring plants with a questionnaire, telephone calls, and a site visit. We obtained secondary data from peer-reviewed literature per CORRIM guidelines (CORRIM 2010). We calculated material and energy balances by a spreadsheet algorithm using data from primary and secondary sources. From these material and energy inputs and reported emission, environmental outputs were estimated by modeling with SimaPro 7 software (PRé Consultants, Amersfoort, Netherlands) (PRé Consultants 2011). SimaPro has been used in previous CORRIM-initiated LCI projects: hardwood lumber (Bergman and Bowe 2008), softwood lumber (Milota et al 2005), softwood lumber (Bergman and Bowe 2010), and softwood plywood (Wilson and Sakimoto 2005). This LCI study conformed to relevant ISO standards (ISO 2006b, 2006c). Results from LCIs can aid in developing environmental product declarations (ISO 2006a, 2007).

Figure 1. Shaded area was selected for life cycle inventory of prefinished engineered wood flooring production in the US.

METHODOLOGY

Scope of the Study

This study covered the life cycle of manufacturing prefinished engineered wood flooring from hardwood logs in the eastern US. LCI data from this study may help conduct an analysis comparing prefinished engineered wood flooring with other wood and nonwood flooring options. The LCI model provided a gate-to-gate analysis of cumulative costs of manufacturing including transportation of raw materials. Analyses included engineered wood flooring's contribution to energy consumption, air pollution, water pollution, solid waste, and climate change. We compared energy consumption of unfinished and prefinished engineered to unfinished solid strip wood flooring.

Functional Unit

Material flows, energy use, and emission data were standardized to a per-unit volume basis for 1.0 m^3 of prefinished engineered wood flooring, the final product of the engineered wood flooring manufacturing process. On the basis of US industry measures, 1 m^3 of prefinished engineered wood flooring equals 100 m^2 (10-mm basis), 1130 ft^2 (3/8-inch basis), or 1.13 thousand ft^2 (3/8-inch basis). In this study, the reference unit was also referred to as the production unit. Wood flooring is usually sold in square feet (ft^2) at various thicknesses. Rough green veneer and rough dry veneer were assumed to be 2.62 and 2.43 m^3/thousand board feet after shrinkage and sanding, respectively (Koch 1985; Bergman 2010). Allocating all material and energy on a per-unit basis of 1.0 m^3 prefinished engineered wood flooring standardized the results to meet ISO standards, thus the unit processes could be used to construct a cradle-to-gate LCI and LCA (ISO 2006b, 2006c; CORRIM 2010).

Reference Flow

Reference flow was defined as oven-dry (OD) mass of 1 m^3 or 100 m^2 (10-mm basis) ready-to-install prefinished engineered wood flooring. In climate-controlled living environments, installed wood flooring typically equilibrates to 8% MC (Bergman 2010).

Data Quality and Data Gathering

Data collection and treatment. We selected the eastern US because the majority of wood flooring production occurs in this region (Hubbard and Bowe 2010). Primary mill data as required by CORRIM Research Guidelines were aggregated to maintain confidentiality of surveyed facilities and to develop a composite engineered wood flooring plant (CORRIM 2010).

Validation of data. We conducted the following analyses to ensure validation of raw and LCI data: 1) comparison of conversion rates from incoming logs to dry veneer to literature values; 2) performed mass balance to track wood material through the entire process; and 3) comparison of gate-to-gate LCI data to a US solid-strip wood flooring gate-to-gate LCI study.

Sensitivity analysis for refining system boundaries. We performed a sensitivity analysis on burning different types of fuel for process energy. This analysis provided changes in environmental impacts based on fuel use.

Data quality statement. Data quality was high because of the extensive and comprehensive questionnaire used to survey the industry (Bergman and Bowe 2011). We collected primary mill data for 2007 from facilities across the eastern US from average technologies ranging from the 1940s to the 2000s that produced 7.366 million m^2 or nearly 19% of total engineered wood flooring production in the US. Approximately 30 engineered wood flooring plants were in the study area (NWFA 2011). We surveyed 5 of the 30 available, about 17%. Most flooring plants produce their own veneer, although one flooring plant used veneer from another vendor. Surveyed facilities provided wood veneer and flooring values on a 3/8-in basis. Based on surveyed mill data, total incoming hardwood log volume of 119,400 m^3 produced total dry veneer production of 67,770 m^3. Adding 35,600 m^3 of purchased dry veneer to that produced on-site resulted in total dry veneer of 103,400 m^3 (10.34 million m^2). Total flooring produced was 73,660 m^3 (7.366 million m^2). We estimated an overall efficiency of 30.1% from logs to prefinished engineered wood flooring. In addition, a log to dried veneer conversion of 40% was calculated. To ensure data completeness, we performed a mass balance and compared results with literature values.

Aggregation. Weighted average was the method of aggregation for primary data from the mill questionnaire. This was also done in previous CORRIM studies with the following equation:

$$\overline{P}_{\text{weighted}} = \frac{\sum_{i=1}^{n} P_i x_i}{\sum_{i=1}^{n} x_i}$$

where $\overline{P}_{\text{weighted}}$ was weighted average of values reported by mills, P_i was reported mill value, and x_i was fraction of the mill's value to total production for that specific value.

Elementary flows. Figure 2 shows wood flow through the system. Manufacturing started with hardwood logs as the raw material and ended with the final product of prefinished engineered wood flooring. Two unit processes of peeling and clipping and trimming, sanding, sawing, and moulding generated the most coproducts (wood residues). In the east, many commercial hardwood species are peeled into veneers for flooring. Often, several species within one species group are mixed; eg the red oak group comprises the following species: scarlet (*Quercus coccinea*), southern (*Q. falcate*), cherrybark (*Q. falcate var. pagodifolia*), laurel (*Q. laurifolia*), water (*Q. nigra*), pin (*Q. palustris*), willow (*Q. phellos*), northern (*Q. rubra*), and black (*Q. velutina*). Other species groups with multiple species are white oak (six): white (*Quercus alba*), swamp white oak (*Q. bicolor*), bur (*Q. macrocarpa*), swamp chestnut (*Q. michauxii*), chestnut (*Q. prinus*), and post (*Q. stellata*); hard maples (two): sugar (*Acer saccharum*) and black (*A. nigrum*); soft maples (two): red (*Acer rubrum*) and silver (*A. saccharinum*); and ash (three): white (*Fraxinus Americana*), black (*F. nigra*), and green (*F. pennsylvanica*).

Allocation Rules

In the wood products industry, a number of coproducts including wood residues are typically produced. In this study, residual wood from manufacturing prefinished engineered wood flooring was often burned on-site for process energy. We expanded the system boundary to include multiple unit processes, however,

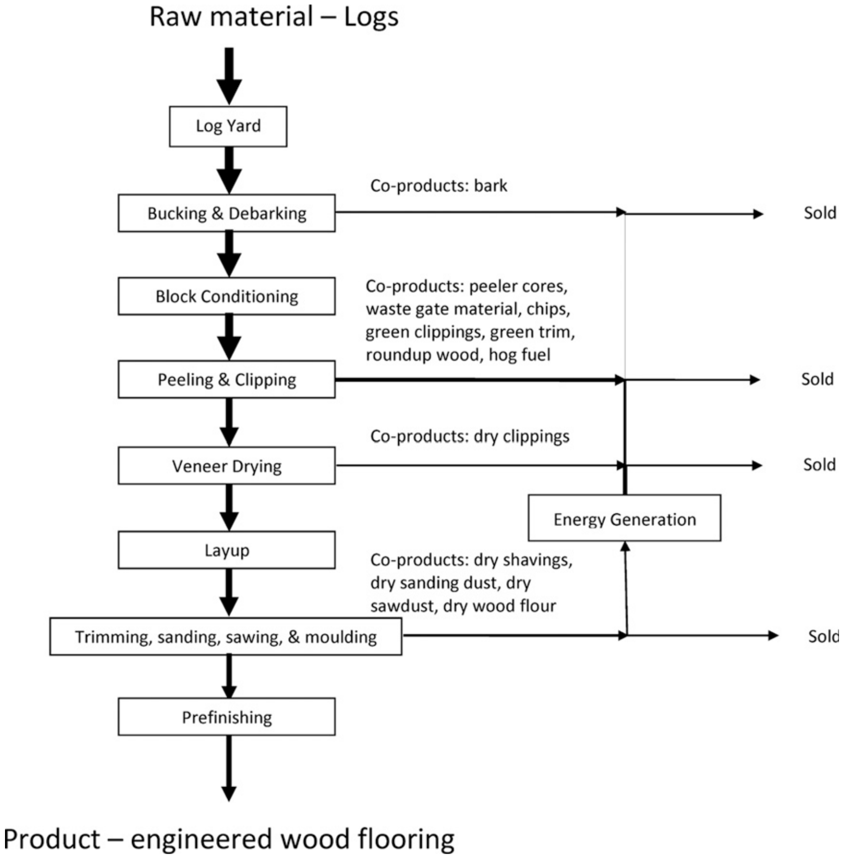

Figure 2. Description of product elementary flows.

coproducts that were sold outside the system boundary required an allocation rule. Mass allocation was chosen because specific gravity of both prefinished engineered wood flooring and associated coproducts was similar (Kodera 2007). This was true for all unit processes. Previous studies on wood products also used mass allocation (Jungmeier et al 2002; Puettmann and Wilson 2005; Werner and Richter 2007; Puettmann et al 2010).

System Boundary Definition

Definition of product system. Eight unit processes were identified—1) logyard; 2) bucking and debarking; 3) block conditioning; 4) peeling and clipping; 5) veneer drying; 6) layup; 7) trimming, sanding, sawing, and moulding; and 8) prefinishing (Fig 3). Trucks transported logs to the veneer mill. Logs were typically stored wet until needed when temperatures were greater than 0°C to prevent staining. Logs were bucked and debarked prior to block conditioning. Block conditioning softened the wood in a hot water bath to allow easier peeling of logs on rotating lathes. After trimming the rotary-sliced veneer sheets to 1.2- × 2.4-m sections, large jet driers dried the thin veneer sheets (plies) to 0-4% MC. The top, bottom, and core veneer plies were usually from different wood species. Press-gluing these veneer sheets together formed a veneer panel, and three- and five-ply panels were common. Before gluing, the sheets were stacked on top of each other with the wood grain running perpendicular to each subsequent sheet (cross-laminated) for dimensional

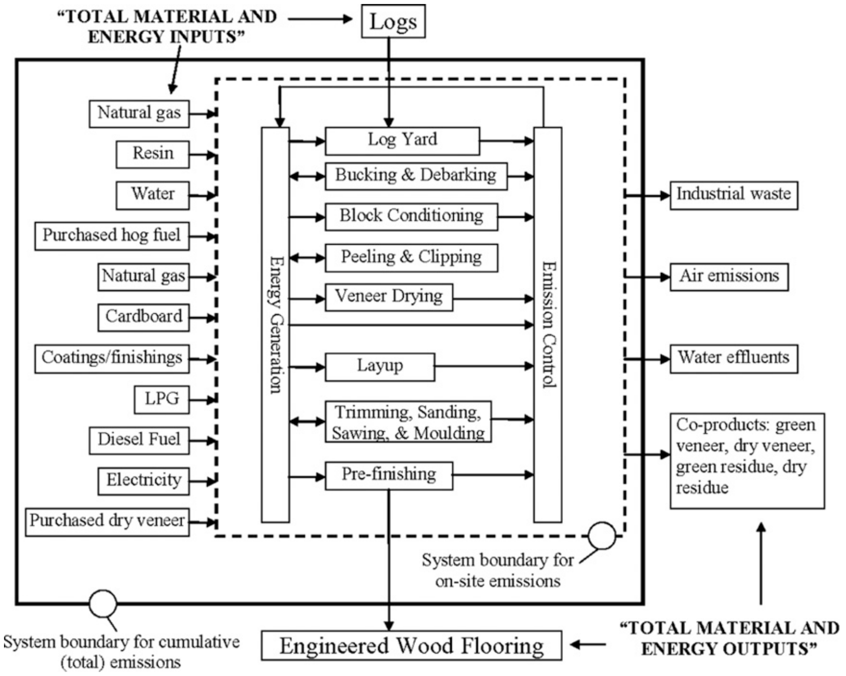

Figure 3. System boundaries for prefinished engineered wood flooring production.

stability. After trimming, machines sanded, sawed, and moulded (profiled) the panels into individual floorboards. These unfinished floorboards were then sanded, stained, and coated, resulting in the final product of prefinished engineered wood flooring. The final product was ready for installation. Final dimensions of flooring ranged from 60-180 mm wide and 6.4-14 mm thick with random lengths.

Decision criteria (cutoff rule, if applicable). All materials expecting to have a significant environmental impact were tracked. We tracked resin and coating materials because we expected that these materials would have a significant environmental impact relative to their mass. Wood material that contributed less than 0.1% by mass to total wood output was not modeled in SimaPro.

Omissions of life cycle stages, processes, and input or output flows. All unit processes within the gate-to-gate system boundary were examined. Human labor and production of machinery and infrastructure were outside system boundaries. Also, forest growth and management, harvesting, product use and maintenance, recycling options, and final disposal life cycle stages were not included in the study.

Project Assumptions and Limitations

Bergman and Bowe (2011) provided detailed assumptions and limitations for determining results of this LCI study (ISO 2006b).

Impact Categories

No impact assessment was conducted because it was beyond the scope of this study.

Critical Review

James Wilson, past vice-president of CORRIM, reviewed the questionnaire used to survey the industry. Maureen Puettmann of WoodLife Consulting, who conducts critical reviews for CORRIM, conducted a review according to ISO standards on the SimaPro module used to develop this report (ISO 2006b, 2006c).

INVENTORY ANALYSIS

Log Yard

This unit process began with transporting logs from the forest landing to the veneer mill and included the following operations: transporting veneer logs from forest landing to the log yard, sorting veneer logs by grades and size, storing logs either wet or dry depending on the season and species, transporting logs in-yard from the point of unloading to log deck storage, and transporting logs in-yard from log deck storage to the veneer mill infeed (debarker and log bucking saw). Inputs included fossil fuel for log haulers and water and electricity for sprinklers. This unit process generated no coproducts. The log wetting process released water emissions. Logging transportation data were required to connect forest resource LCI to prefinished engineered wood flooring LCI.

Debarking and Bucking

This unit process began with logs at the debarker and included mechanically removing the bark from the logs and cross-cutting long logs to make wood “blocks” for peeling (cutoff saw). Inputs included electricity to operate the debarker and saw and diesel fuel for the log haulers. Coproducts generated included green bark and some green wood waste including material lost as end cuts. Green wood residues were either ground into wood fuel that was burned on-site or sold as mulch. In this study, surveyed mills listed roughly 50% of the bark as hog fuel.

Block Conditioning

Wood blocks were heated in vats with either hot water or direct steam to soften the log to improve quality of the peeled veneer. Inputs included steam or hot water and electricity for the vats and fossil fuel for equipment to load and unload vats. This unit process produced no coproducts. Emissions associated with this unit process included air and water emissions from boilers providing heat for vats.

Peeling and Clipping

A rotary lathe sliced the hot, softened veneer blocks into thin veneer sheets, and a clipper trimmed the sheets to size. Inputs included electricity to run lathes, conveyors, clippers, hog fuel grinders, and waste gate equipment and fossil fuel to transport veneer sheets to veneer dryers. Coproducts included green roundup wood, green peeler cores, green wood chips, green waste gate material, and green veneer clippings. Roundup wood was the wood material lost from peeling the block to create a cylindrical shape. Green roundup wood and green veneer clippings were ground into wood fuel that was burned on-site. Ground green wood fuel was also listed as hog fuel. Green peeler cores, green chips, and green waste gate material were sold.

Veneer Drying

Jet dryers dried the green veneer sheets to 0-4% MC. Inputs included electricity to run fans, steam or hot oil for heating the coils inside the dryers, and fossil fuel consumed in forklifts transporting veneer from the peeling and clipping operation to the veneer drying process. Veneers were clipped after drying. Coproducts included dry clippings. Air emissions occurred. This unit process generated air emissions as wood dried and dryer temperature rose and resulted in large amounts of VOCs compared with other unit processes. Other emissions associated with this unit process included air emissions from boilers or direct-fired burners providing heat for dryers.

Layup

This unit process involved bonding thin veneer sheets, also called plies, together with resin to form panels. The resins were urea–formaldehyde and polyvinyl acetate. Plies were stacked on top of each other with the wood grain oriented perpendicular to the previous sheet for dimensional stability. Depending on the resin, pressure and heat were applied to the sheets to cure the resin and bond the sheets to form veneer panels. Three- to five-ply veneer panels are common for engineered wood flooring. Inputs included heat and electricity to apply resin and run presses and fossil fuel for forklifts and for transporting material to the trimming, sanding, sawing, and moulding unit process. Other inputs were water to produce the resin and diesel fuel to transport dry veneer from veneer mills. This unit process generated no coproducts. The pressing and heating processes released air emissions as the resin cured. In addition, emissions associated with this unit process included air emissions from boilers providing heat for panel presses.

Trimming, Sanding, Sawing, and Moulding

Veneer panels were trimmed to standard dimensions, 1.2 × 2.4 m. Trimmed panels were sawn into individual boards and sanded. After sanding, the boards were moulded (profiled) into tongue and groove flooring of random lengths. Inputs included electricity for the trim saw, the gang rip saw, sanding, and hog fuel grinding and fossil fuel to transport the unfinished wood flooring to the prefinishing unit process. Coproducts included dry trim material, dry sanding dust, dry sawdust, and dry shavings.

Prefinishing

Prefinishing unfinished wood flooring protected the surface. This unit process included the following operations: sanding, priming, staining, filling, curing, sealing, and topcoating. Sanding the wood prepared the surface for priming, staining, filling, sealing, and topcoating. The primer coat promoted adhesion of other materials and was UV-cured. Staining material included water-based, solvent-based, and UV-cured types. Rollers typically applied the stain, filler, sealer, and topcoat. Solvents cleaned the rollers. All filler, sealer, and topcoats were UV-cured. Aluminum oxide added to the finish increased surface durability. After prefinishing, facilities shipped ready-to-install flooring in small cardboard boxes. Inputs included steam for the stain-drying ovens; electricity for UV-curing ovens, conveyors, and wood dust collectors; and cardboard for boxing. Air emissions released included sanding dust, PM10, hazardous air pollutants, and VOCs.

Auxiliary Processes

Energy generation. Wood, propane, and natural gas were burned for thermal process energy. Green wood residue from peeling and clipping and dried wood residue from trimming, sanding, sawing, and moulding generated almost all the thermal energy produced and used at the plant. This energy was typically in the form of steam used for presses, jet dryers, ovens, and facility heating. Also, this auxiliary process provided heat for use in other parts of the veneer mill and flooring plant. This process involved the following operations: fuel handling; adding water to the boiler (ie make-up water); adding chemicals to either the boiler or the steam lines; distributing steam and electricity; and treating process air, liquids, and solids.

Outputs of this auxiliary process were steam and hot water from boilers, combustion gases for drying, solid waste (wood ash), and air emissions (eg CO_2, CO) from combustion. Also, production of grid electricity used on-site released emissions off-site. An environmental profile for grid electricity was included in this analysis.

Emission controls. This auxiliary process decreased the amount of air emissions released. Wood dust collectors collected particulate and PM10 from sanding and prefinishing operations. Air handlers prevented release of VOCs from prefinishing and veneer drying. Input included electricity.

RESULTS

Product Yields

Mass and energy values and the environmental profile for making prefinished engineered wood flooring were obtained by surveying four veneer mills and five flooring plants in the eastern US. These facilities provided detailed survey production data on mass flow, energy consumption, types of fuel, and emission data. The survey-weighted average data were modeled in SimaPro 7 to find nonwood raw material use and emission data. Bergman and Bowe (2011) provided the SimaPro input data.

Weighted average annual production for the prefinished engineered wood flooring facilities was 19.8 thousand m^3 with a range of 6.1-31.1 thousand m^3. Other weighted average mill features included log diameter (small end, inside bark) of 380 mm with a range of 330-460 mm. Also, wood chips were the largest proportion of wood residue produced at 533 OD kg per production unit (Table 1). Flooring plants purchased 177 OD kg of dry veneer per production unit. Species veneered were red oak (roughly half), white oak, hard and soft maple, yellow poplar, yellow birch, black cherry, ash, sweetgum, pecan, hickory, hackberry, elm, and some miscellaneous species.

Table 1. Wood mass balance for 1.0 m^3 of prefinished engineered wood flooring (weighted average values in oven-dried kilograms).

	Wood mass balance			
Material	In	Out	Boiler fuel	Sold
Green logs (white wood only)	1255			
Green logs (bark only)[a]	66.9			
Dry veneer (purchased)	177			
Green bark		66.9	6.0	60.9
Green roundup wood		2.8	2.8	0.0
Green peeler cores		0.2	0.0	0.2
Green veneer clipping		0.6	0.6	0.0
Green trim		0.6	0.6	0.0
Green chips		532.8	0.1	532.7
Green hog fuel		175.3	175.3	0.0
Green waste gate material		0.1	0.0	0.1
Dry clipping		7.6	4.6	3.1
Dry sawdust		106	2.7	103
Dry shavings		11.1	0.8	10.3
Dry sanding dust		17.8	0.2	17.6
Engineered wood flooring		578		
Sum	1500	1500	194	728

[a] About half the bark was included under green hog fuel.

For the mass balance, the LCI study examined eight main unit processes and the overall process to track material flows. Using a weighted average multiunit approach, 1255 OD kg of incoming hardwood logs with a green density of 944 kg/m^3 and 177 OD kg of purchased rough dry veneer with a density of 613 kg/m^3 produced 1.0 m^3 of prefinished engineered wood flooring. Boilers burned 194 OD kg of both green and dry wood fuel produced on-site (Table 1). Overall, a difference of 3.7% was calculated based on overall mass balance that included intermediate products such as rough green and rough dry veneer.

Most veneer mills in the US track log breakdown to find mill efficiency. The veneer recovery factor (VRF) is one way to track log breakdown. In this study, VRF quantified productivity as weight of veneer (minus resin) produced divided by total weight of incoming wood in log form. A VRF of 42.6% was calculated. Wilson and Sakimoto (2004) showed a VRF of 51 and 50% for production of softwood plywood in the Pacific Northwest and the Southeast, respectively.

NONWOOD INPUTS

Water Consumption

Water use was mainly for sprinkling logs, steaming vats, and boiler make-up water. Surface and ground water consumption of 972 and 2840 L/m^3 of prefinished engineered wood flooring were calculated, respectively. Water consumption was broken down into the following unit processes: logyard (30%), block conditioning (40%), layup (10%), and auxiliary energy generation (20%).

Transportation Data

On-site transportation of wood stock was a major fuel consumer with off-road diesel having the greatest consumption. On-site transportation included forklifts, front-end loaders, trucks, and other equipment used within the system boundary of the facility. Total diesel consumption was 11.3 L/m^3 of prefinished engineered wood flooring. Diesel consumption was about three times the rate of propane and gasoline combined. Gasoline and propane use was 0.57 and 3.10 L/m^3, respectively. Diesel consumption was comprised of off-road fuel used on-site and on-road fuel used to haul dry veneer to flooring plants. Off-road and on-road diesel use was 7.0 and 4.3 L/m^3, respectively.

Resource Transportation

Resource transportation data considered many resources (Table 2). Distance traveled had a large effect on results, especially for dry veneer material. In this study, nonpurchased and purchased dry veneers traveled about three to five times farther than logs did. Therefore, log transportation data of 467 t-km were close to the average value of 558 and 300 t-km for nonpurchased and purchased dry veneer, respectively. Logs were heavier, however, at 85% MC, whereas dry veneer was lighter at 6% MC. Surveyed mills produced the nonpurchased dry veneer. Stains and coatings had minimal effect on transportation because of the small volume consumed in the manufacturing process.

Table 2. Resource transportation.

Resource	Distance (km)	Transportation (t-km)
Logs (white wood only)	201	467
Bark	201	25
Purchased wood fuel	165	24
Dry veneer (nonpurchased)	1040	558
Dry veneer (purchased)	535	300
Resin	477	48
Stain	205	1
Coatings	205	2

MANUFACTURING ENERGY

Overall

Prefinished engineered wood flooring production required both electrical and thermal energy for processing logs into flooring. All the thermal energy was produced directly on-site, whereas electricity was produced indirectly (ie off-site) and delivered through a regional power grid. Electrical energy was required for all unit processes, whereas most thermal energy was required for block conditioning, veneer drying, layup, and prefinishing processes. Total electrical consumption was 1110 kWh/m^3 prefinished engineered wood flooring (Table 3). Total process energy (unallocated) of 6.42 GJ was consumed per cubic meter of prefinished engineered wood flooring. Wood fuel at 300 OD kg or 6.26 GJ/m^3 contributed 97.6% of process thermal energy required with the remainder from propane (2.2%) and natural gas (0.2%).

Electrical

For unit processes and auxiliary unit processes (energy generation, emission controls [veneer mill], and emission controls [flooring plant]), distribution of electrical energy consumption is

Table 3. Material and energy consumed on site to produce 1.0 m^3 of prefinished engineered wood flooring (SimaPro input values).[a]

Fuel type	Quantity (units/m^3)
Fossil fuel[b]	
Natural gas	0.30 m^3
Propane	5.36 L
Electricity[c]	
Off-site generation	1110 kWh
On-site transportation fuel[d]	
Off-road diesel	7.01 L
On-road diesel[e]	4.26 L
Gasoline	0.57 L
Propane	0.04 L
Renewable fuel[f]	
On-site wood fuel	194 kg
Purchased wood fuel	106 kg
Water use	
Surface water	972 L
Ground water	2840 L

[a] Includes fuel used for electricity production and for transportation (unallocated).

[b] Energy values were determined using their higher heating values in MJ/kg: 54.4 for natural gas and 54.0 for propane.

[c] Conversion unit for electricity is 3.6 MJ/kWh.

[d] Energy values were determined using their higher heating values in MJ/kg: 45.5 for off-road and on-road diesel and 54.4 for gasoline.

[e] Transportation of panels and veneer between facilities; not accounted for in other transportation data.

[f] Values given in oven-dry weights (20.9 MJ/OD kg).

shown in Table 4. Total electrical consumption was 1110 kWh/m^3. For auxiliary unit processes, the greatest electrical consumption occurred in the emission control (flooring plant) process with 335 kWh/m^3, about 30% of the total. Total electrical consumption for hardwood plywood production was 462 kWh/m^3. Hardwood plywood production included all unit processes from incoming hardwood logs to layup. For hardwood plywood production, layup consumed roughly 44% of the total at 201 kWh/m^3. Wilson and Sakimoto (2004) reported electrical consumption of 138 kWh/m^3 for Pacific Northwest softwood plywood, approximately 30% of hardwood plywood production.

Off-site generation of electrical power affected environmental impact because of all the different fuels used to generate power. Average composition of (off-site) electrical generation for the eastern US grid was taken from SimaPro (ie US LCI Database) (PRé Consultants 2011). The most significant electric power contributor in the Eastern region was coal with 58.9% of total electrical utility power including both bituminous and lignite coals. Other fuel sources were nuclear, natural gas, petroleum, hydro, biomass, and unspecified fossils, which provided 22.7, 10.1, 3.3, 2.9, 1.6, and 0.5%, respectively. Wind power contributed less than 0.05% to the grid.

Heat

A total process energy (unallocated) of 6.42 GJ was consumed per cubic meter prefinished engineered wood flooring. Unit processes of block conditioning, veneer drying, layup, and stain drying consumed 1.521 GJ (23.7%), 3.773 GJ (58.8%), 0.723 GJ (11.3%), and 0.401 GJ (6.2%) of process thermal energy, respectively. Facility heating was divided evenly among these four processes. For an energy check, we estimated a literature value for block conditioning of 1.64 GJ/m^3 assuming frozen oak logs heated to 100°C, boiler efficiency of 75%, and boiler vat efficiency of 25% caused by using live steam (Steinhagen 2005). In addition, a previous CORRIM study on southeast plywood showed a veneer drying value of 1.61 GJ/m^3 (Wilson and Sakimoto 2004). Hardwood plywood may take two to three times more energy for drying than softwoods because hardwood contains more water because of its higher density.

Table 4. Electricity consumption broken down by unit processes.

Unit process	%	kWh/m^3
Bucking and debarking	8.0	89
Block conditioning	2.4	26
Peeling and clipping	11.9	133
Veneer drying	1.2	13
Layup	18.1	201
Trimming, sanding, sawing, and moulding	6.0	67
Prefinishing	6.0	67
Energy generation	11.9	133
Emissions control (veneer mill)	4.4	49
Emission controls (flooring plant)	30.1	335
Total	100	1110

ENVIRONMENTAL IMPACTS

SimaPro 7 modeled output factors during the manufacturing process with major consumption of raw materials, other than wood, for electrical generation. Other major raw materials used, other than logs processed into veneer, were coal, purchased wood fuel (residue), natural gas, crude oil, and limestone with allocated values of 352, 105, 75.6, 74.8, and 14.8 kg per production unit, respectively. A wood log volume of 1.43 m^3 was allocated to produce 1.0 m^3 prefinished engineered wood flooring (Table 5). Limestone (which helps remove sulfur dioxide emitted from burning coal) and most of the coal were used to produce off-site electricity; oil and natural gas were for off-site electricity, resins, and finishing materials; and thermal energy used on-site. Veneer mills and flooring plants burned purchased wood fuel for thermal energy use on-site.

Table 6 shows allocated cumulative energy of making 1.0 m^3 of prefinished engineered wood flooring. For cumulative energy allocated to prefinished engineered wood flooring, a value of 23.0 GJ/m^3 was found. Coal used to produce electricity provided by far the largest portion of energy needed, mostly because of the intensive

Table 5. Raw materials consumed during production of prefinished engineered wood flooring—cumulative, allocated gate-to-gate life cycle inventory values (SimaPro output values).[a]

Raw material[b]	Quantity[c] (units/m^3)
Logs at mill gate[d]	1.43 m^3
Water, well, in ground[e]	2.51 m^3
Water, process, surface[e]	6.35 m^3
Wood fuel	105 kg
Coal, in ground[e]	352 kg
Gas, natural, in ground[e]	75.6 kg
Oil, crude, in ground[e]	74.8 kg
Limestone, in ground[e]	14.8 kg
Energy, from hydro power	3.74 kWh
Energy, unspecified	0.41 kWh
Uranium, in ground[e]	0.0106 kg

[a] Includes fuel used for electricity production and for log and purchased wood fuel transportation (allocated).

[b] Values are allocated and cumulative.

[c] Energy values were found using higher heating values 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] Amount of wood in log form allocated to final product; no shrinkage was taken into account from the drying process. Value contains no coproducts but does include amount of on-site-generated wood fuel allocated to the flooring.

[e] Materials as they exist in nature and have neither emissions nor energy consumption associated with them.

Table 6. Cumulative energy (higher heating values) consumed during production of prefinished engineered wood flooring—cumulative, allocated gate-to-gate life cycle inventory values (SimaPro output values).[a]

Fuel[b,c]	kg/m^3	MJ/m^3
Wood fuel	105	2,200
Coal, in ground[d]	352	9,220
Gas, natural, in ground[d]	75.6	4,110
Oil, crude, in ground[d]	74.8	3,400
Energy, from hydro power[e]	—	13
Uranium, in ground[d]	0.0106	4,040
Energy, unspecified[e]	—	1
Total		23,000

[a] Includes fuel used for electricity production and for log and purchased wood fuel transportation (allocated).

[b] Values are allocated, cumulative, and based on higher heating values.

[c] Energy values were found using their higher heating values 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.

[e] No mass units are assigned to hydro and unspecified energy.

electrical energy needed for peeling and clipping (11.9%), layup (18.1%), and emission controls associated with prefinishing (30.1%).

Two different LCI scenarios for manufacturing prefinished engineered wood flooring were evaluated based on five veneer mills and four flooring plants surveyed—allocated cumulatively and allocated on-site. The method for evaluating the two scenarios followed ISO 14040 standards and CORRIM guidelines. Allocated accumulative scenarios examined all emissions for electricity and thermal energy generation that were required to produce 1.0 m^3 of prefinished engineered wood flooring starting with hardwood logs at the mill gate. These emissions involved the cradle-to-gate resource requirements (production and delivery) of grid electricity, fossil fuels, and purchased wood fuel used in the boiler and fossil fuels used in yard equipment such as forklifts. Also, emission data for on-site combustion of the two latter materials and wood fuel generated on-site were included. Transportation of logs (including bark) to the mill gate was included in the cumulative system boundary. The allocated on-site scenario only includes emissions from combustion of all fuels used at the mills and flooring plants, therefore it did not involve manufacturing and delivery of materials, fuels, and electricity consumed at the mill.

Table 7 shows the lower environmental impact of on-site compared with cumulative emissions for facilities surveyed. CO_2 and particulates are typically measured, although other emissions are frequently monitored from boilers to ensure regulatory compliance. CO_2 emissions are separated by two fuel sources, biogenic (biomass-derived) and anthropogenic (fossil fuel-derived). Accumulative total emission values of 623 and 1050 kg were reported from SimaPro for CO_2 (biogenic) and CO_2 (fossil), respectively (Table 7). The percentage of biogenic CO_2 to total CO_2 increased from 37.3 to 64.8% from the total (cumulative) to on-site scenarios. Emissions of VOC gases were roughly the same at approximately 1 kg regardless of scenario, indicating that veneer (wood) drying was a significant contributor to the overall amount of VOCs.

Material and energy resources consumed to manufacture 1 m^3 of prefinished engineered wood flooring are shown in Table 3. These LCI

Table 7. Life cycle inventory results for total cumulative and on-site emissions on a per-unit basis of prefinished engineered wood flooring (allocated).

Substance	Total cumulative (kg/m^3)	On-site (kg/m^3)
Water emissions		
Biological oxygen demand (BOD)	1.09	1.06
Cl^-	14.9	7.9
Suspended solids, unspecified	0.933	0.591
Oils, unspecified	0.0911	0.0865
Dissolved solids	12.6	3.94
Chemical oxygen demand (COD)	1.52	1.45
Other solid materials[a]		
Waste in inert landfill	28.4	28.4
Recycled material	9.34	9.34
Solid waste[b]	41.0	41.0
Air emissions		
Acetaldehyde	0.217	0.217
Acrolein	4.90×10^{-5}	1.10×10^{-5}
Benzene	0.00232	0.00214
Carbon dioxide (biomass)	623	610
Carbon dioxide (fossil)	1050	331
Carbon monoxide	5.57	5.02
Methane	2.65	1.211
Formaldehyde	0.0400	0.0398
Mercury	4.84×10^{-4}	1.39×10^{-5}
Naphthalene	6.99×10^{-4}	9.96×10^{-4}
Nitrous oxides	3.76	1.61
Nonmethane, volatile organic compounds (NMVOC)	0.579	0.502
Organic substances, unspecified	0.0805	0.0797
Particulate (PM10)	0.138	0.138
Particulate (unspecified)	0.610	0.171
Phenol	0.0192	0.0192
Sulfur dioxide	5.05	0.558
VOC	1.04	0.999

[a] Includes solid materials not incorporated into the product or coproducts and leaving the system boundary.

[b] Solid waste is mostly boiler ash from burning wood. Boiler ash is either spread as a soil amendment or landfilled depending on the facility.

Table 8. Fuel and electrical energy used on site to produce a 1 m^3 of prefinished engineered wood flooring.

	Energy use at mill	
	Unallocated (MJ/m^3)	Allocated (MJ/m^3)
Fossil fuel[a]		
Natural gas	11.4	6.62
Propane	143	82.9
Electricity[b]		
Off-site generation	4010	2330
On-site transportation fuel[c]		
Off-road diesel	271	110
On-road diesel	165	66.9
Gasoline	19.9	8.09
Propane	167	67.9
Renewable fuel[d]		
On-site wood fuel	4050	2350
Purchased wood fuel	2220	1290
Total	11,000	6300

[a] Energy values were determined using their higher heating values in MJ/kg: 43.3 for fuel oil #1 and #2.

[b] Conversion unit for electricity is 3.6 MJ/kWh.

[c] Energy values were determined using their higher heating values in MJ/l: 38.7 for off-road diesel, 26.6 for propane, and 34.8 for gasoline.

[d] Values given in oven-dried weights (20.9 MJ/OD kg).

input values were unallocated and were entered into SimaPro 7 to find the environmental impact of manufacturing 1 m^3 of prefinished engineered wood flooring. Table 8 lists on-site energy values unallocated and allocated to planed dry lumber. Unallocated values were calculated from material and energy resources found in Table 3 and were the sum of all fuel and electricity inputs to the process. Allocated on-site energy use is roughly 57% of the total unallocated on-site use. Material and energy consumed at the mill for SimaPro 7 gave LCI outputs allocated to manufacturing prefinished engineered wood flooring, not to associated wood coproducts. Using the total difference between unallocated and allocated values, we calculated 4.70 GJ of energy used at the mill allocated to coproducts.

Table 9 shows the difference by type of wood flooring for cumulative energy (allocated). Results showed a cumulative allocated value for manufacturing prefinished engineered wood flooring from the forest road to the final product leaving the flooring plant of 23.0 GJ/m^3. Cumulative allocated value considers electrical efficiency of grid power provided. Unfinished engineered wood flooring showed a cumulative allocated value of 13.6 GJ/m^3. Prefinished

Table 9. Cumulative energy (higher heating values) consumed during production of prefinished engineered wood flooring compared with unfinished engineered and solid strip wood flooring—cumulative, allocated gate-to-gate life cycle inventory values (SimaPro output values).[a]

	Unfinished solid strip flooring[c]	Engineered wood flooring	
		Unfinished	Prefinished
Fuel[b] (MJ/m^3)			
Biomass	4,200	1,720	2,200
Coal	748	4,990	9,220
Natural gas	934	2,930	4,110
Crude oil	557	2,580	3,400
Hydro	9	4	13
Uranium	48	1,360	4,040
Energy, unspecified	7	1	1
Total	6,500	13,600	23,000

[a] Includes fuel used for electricity production and for log and purchased wood fuel transportation (allocated).

[b] Based on higher heating values. Energy values were found using their higher heating values 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.

[c] Puettmann et al (2010).

consumed more energy than unfinished engineered wood flooring, roughly 60% more. Much of this increase in energy resulted from electrical consumption in emission control devices used to prevent release of VOCs. These devices consumed approximately 30% (335 kWh/m^3) of total electricity needed for the entire manufacturing process, whereas unfinished solid strip flooring consumed 182 kWh/m^3 allocated from gate to gate (Hubbard and Bowe 2010). Resin usage also increased environmental loading as shown when comparing unfinished engineered with unfinished solid strip wood flooring. Unfinished solid strip flooring cumulative energy consumption of only 6.50 GJ/m^3 was roughly half that of unfinished engineered wood flooring. Also, most of that energy was derived from biomass, not fossil fuels.

Allocated cumulative energy values comparing various wood flooring materials in different units are shown in Table 10. Unfinished solid strip flooring in the US had the lowest cumulative energy value with 9.89 MJ/kg, about 50% that of unfinished engineered wood flooring on a mass (ie volume) basis. Converting to MJ/m^2 (production unit) indicated that the two unfinished wood flooring materials have similar values. However, prefinishing the final product resulted in a 60% increase in energy consumption, exactly the same result as previously mentioned.

Table 10. Cumulative energy consumed during production of various wood floorings (allocated).

Type	Density[a] (kg/m^3)	Energy (MJ/kg)	Weight (kg/m^2)	Energy (MJ/m^2)
Prefinished engineered wood[b]	656	35.0	6.56	230
Unfinished engineered wood[b]	643	21.1	6.43	136
Unfinished solid strip (US)[c]	657	9.89	12.5	123

[a] Oven-dried.

[b] Wood material had 9.5-mm thickness.

[c] Hubbard and Bowe (2010); 19-mm thickness.

CARBON BALANCE

Carbon impact was determined by estimating values of carbon found in wood and bark as described in previous studies (Birdsey 1992; Skog and Nicholson 1998) using a mixture of hardwood roundwood values for the Eastern US. We used a mixed hardwood factor of 305.1 kg/m^3 of wood material and a carbon content of 51.7% with an incoming log wood mass of 1255 OD kg/m^3 prefinished engineered wood floor ing to calculate carbon balance. Resins and coating processes were not included. Total carbon input and output of 831 and 872 kg/m^3 prefinished engineered wood flooring were found (Table 11), resulting in a difference of 4.4%. One meter cubed of prefinished engineered wood flooring stored 1100 kg CO_2 equivalents as a final product.

SENSITIVITY ANALYSIS

A sensitivity analysis was completed per ISO 14040 standards in SimaPro to model the effects of using different quantities of fuel sources for thermal energy generation. Sensitivity analysis can be useful to understand how various process parameters contribute to environmental output factors. For instance, in prefinished engineered wood flooring manufacturing, heat is used in several subprocesses. A combination of wood, natural gas, and propane is used to generate the

Table 11. Tracking of wood-based carbon inputs and outputs for prefinished engineered wood flooring.

Substance[a]	Wood (kg/m^3)	Elemental carbon (kg/m^3)
Input		
Logs	1260	649
Bark[b]	67	35
Purchased dry veneers	177	92
Purchased wood fuel	106	55
Sum carbon in	1610	831
Output		
Prefinished engineered wood flooring	578	299
Coproducts[c]	728	376
Solid emissions	41	21
Air emissions	633	176
Sum carbon out	1980	872

[a] Wood-related carbon and its emissions.

[b] Multiplying (mass of wood flooring) × (carbon content) × (carbon to CO_2 conversion) = 578 kg × 51.7% × 44/12 = 1100 kg CO_2 equivalents.

[c] Bark leaves system both as wood fuel and a coproduct (mulch).

heat. Changing fuel sources, also referred to as fuel switching, can have a significant effect on emission type and amount. This sensitivity analysis compared effects of using the "base" fuel mix to using 1) all on-site-generated wood fuel (mostly green hog fuel from the peeling and clipping process); and 2) all propane as the fuel input. Propane is chosen because it burns cleaner than fuel oil and is abundantly available domestically.

Alternative Fuel Sources

The base fuel mix in this study included three fuel sources with wood fuel and propane supplying the majority of the energy. Natural gas contributed less than 1%. Based on survey data, the original model assumed that 97.6% of the fuel used was wood fuel (63.1% produced on-site [194 kg] and the remainder purchased [106 kg]) and 2.2% was propane. Most mills use only one or two types of fuel, whereas the base mix resulted in a weight-averaged composite model incorporating different fuel sources taken from primary mill data for the five veneer mills and four flooring plants. In this sensitivity analysis, two alternative fuel-use scenarios were created for comparison with the composite mill or base scenario. One alternative assumed consumption of only on-site (generated) wood fuel for all thermal energy by increasing the initial base value of 194 to 307 OD kg to generate 6.42 GJ/m^3 of prefinished engineered wood flooring. In the second alternative fuel-use scenario, 100% propane, propane use increased from base value of 5.4 to 241 L to provide all necessary heat for the facility.

Three Fuel-Source Scenarios

This sensitivity analysis examined three scenarios for heat generation: base fuel mix, 100% propane, and 100% on-site (generated) wood. All three scenarios included emissions from cradle-to-gate resource requirements (production and delivery) of grid electricity. The following three scenarios were modeled using SimaPro to find differences in emissions: 1) 100% propane compared with base hardwood lumber fuel mix that used both propane and wood fuel; 2) 100% on-site (generated) wood fuel compared with base hardwood lumber fuel mix that again had no fuel changes; and 3) 100% propane compared with 100% on-site (generated) wood fuel.

Sensitivity Analysis Results

Table 12 presents the summary of the three fuel-use scenarios with a partial list of air emissions for the Eastern US. In scenarios 1 and 2, a negative percentage difference number indicated that the alternative fuel source released fewer emissions than did the base model. A positive percentage difference means that the base or original model released fewer emissions. Scenario 1 indicated that less particulate (PM10), solid waste, acetaldehyde, and biogenic CO_2 but more fossil CO_2, nonmethane VOC, and NOx were produced when burning 100% propane compared with the base fuel mix (original). Scenario 2 showed slightly more biogenic CO_2, both types of particulate, acetaldehyde, benzene, naphthalene, and phenol but less fossil CO_2 and NOx were produced when burning 100% wood fuel compared with the base fuel mix (original). In scenario 3, a negative number indicates that the all propane case released fewer emissions

Table 12. Sensitivity analysis for manufacturing prefinished engineered wood flooring.

	Fuel distribution (kg/m^3 planed dry lumber)			Difference (%)		
Substance	100% propane	100% wood fuel[a]	Original (base)	Scenario 1—100% propane to original	Scenario 2—100% wood fuel to original	Scenario 3—100% propane to 100% wood fuel
Acetaldehyde	2.15E-01	2.18E-01	2.17E-01	−1.2%	0.5%	−1.7%
Benzene	1.41E-03	2.44E-03	2.40E-03	−51.9%	1.7%	−53.5%
CO_2 (biogenic)	5.59E+01	6.41E+02	6.24E+02	−167.1%	2.7%	−167.9%
CO_2 (fossil)	1.45E+03	1.06E+03	1.06E+03	30.6%	0.1%	30.4%
CO	3.61E+00	5.73E+00	4.39E+00	−19.4%	26.6%	−45.4%
Formaldehyde	3.80E-02	4.02E-02	4.00E-02	−5.1%	0.5%	−5.6%
Methane	2.20E+00	1.72E+00	2.67E+00	−19.5%	−43.4%	24.3%
Naphthalene	5.00E-05	7.18E-04	6.99E-04	−173.3%	2.7%	−174.0%
Nitrogen oxides	4.10E+00	3.79E+00	3.80E+00	7.5%	−0.5%	7.9%
Nonmethane, VOC	8.22E-01	5.85E-01	5.87E-01	33.3%	−0.3%	33.6%
Organic substances, unspecified	3.55E-02	8.18E-02	8.05E-02	−77.5%	1.7%	−78.9%
Particulate (PM10)	9.19E-02	1.40E-01	1.38E-01	−40.3%	1.1%	−41.4%
Particulate (unspecified)	6.31E-01	6.19E-01	6.10E-01	3.3%	1.4%	2.0%
Phenol	8.31E-03	1.95E-02	1.92E-02	−79.1%	1.8%	−80.6%
Sulfur dioxide	2.16E+00	5.15E+00	5.11E+00	−81.2%	0.8%	−81.9%
VOC	1.06E+00	1.05E+00	1.04E+00	1.3%	0.4%	0.9%
Solid waste	1.67E+01	4.18E+01	4.14E+01	−84.8%	1.1%	−85.7%

[a] All wood fuel used was generated on-site.
VOC = volatile organic compounds.

than the all on-site-produced wood fuel case, and a positive percentage number means that all on-site-produced wood fuel models released fewer emissions. Scenario 3 highlighted the increase of fossil CO_2, nonmethane VOC, and NOx along with less particulate (PM10) and biogenic CO_2 produced compared with scenario 1. For all three scenarios, amount of VOC produced was similar regardless of fuel used because most VOC originated in the actual drying of the veneer and during panel-making and prefinishing.

DISCUSSION

Results showed that two of the eight unit processes had the greatest impact regarding process thermal energy consumption. Veneer drying and block conditioning consumed more than 80% of process energy produced on-site. Therefore, these two unit processes had the greatest potential for energy decrease and should be the area of process improvements for the wood flooring and veneer industry. Wood drying processes such as veneer drying consume considerable energy to produce a reasonably dry dimensionally stable product for installation. Decreasing energy consumption also would be of great benefit to mills in terms of financial benefits (decreased costs).

This study indicated that processing hardwood species into plywood consumed two to three times more process energy than softwood plywood production. Other studies on drying hardwoods in conjunction with manufacturing wood products also showed that hardwoods consumed significantly more process energy than softwoods on a per-unit production basis (Puettmann et al 2010; Bergman and Bowe 2010; Hubbard and Bowe 2010).

A tradeoff occurred for prefinishing engineered wood flooring on-site. Additional electricity for emission controls of VOCs emitted during prefinishing had a large environmental impact up front. Prefinishing emission controls consumed more than 30% of total electricity consumed during the manufacturing phase. However, environmental impact of prefinishing on-site would probably be less than that of finishing engineered wood flooring after installation when other factors are included besides energy consumption.

This is because of controlling emissions at flooring plants instead of allowing uncontrolled release of VOCs when finishing the installed engineered wood floor at a residential or commercial building.

In this LCI study, different physical units give different results, therefore, selecting the proper unit for comparison is critical for an accurate assessment. Unfinished engineered wood flooring consumes roughly the same allocated cumulative energy as unfinished solid strip flooring on an area basis, whereas energy consumption for unfinished engineered is about 200% of unfinished solid strip on a volume basis. Regardless, most of the allocated cumulative energy for unfinished engineered wood flooring is derived from fossil fuels because of the large amount of electricity consumed during manufacturing, unlike solid strip.

For a LCI to be consistent within the region studied and adequately represent industry data, both the surveyed facilities and all of the industry facilities with the surveyed facilities included should be of similar size. The average surveyed flooring facility was 19.8 thousand m^3, whereas the industry average was 20.3 thousand m^3 (CRI 2009). Average production for surveyed facilities and for the industry was roughly the same, indicating high data quality representation from the surveyed facilities.

The sensitivity analysis showed how the emission profile changes because of fuel switching. Fuel switching occurs frequently in industry based on fuel costs. Burning only propane adds significant fossil GHGs to the atmosphere. Fossil GHGs are a significant source of the current climate change phenomenon. Burning additional wood fuel, a typically cheaper fuel, lowers fossil GHG emissions, however it potentially adds more particulate matter if emission control devices are not effective.

CONCLUSIONS AND RECOMMENDATIONS

The following main conclusions are based on the LCI.

Converting flooring to an area basis provides a more accurate in-use comparison on energy consumption. Making engineered instead of solid strip flooring requires twice the energy on a volume basis. However, converting to an area basis results in similar energy usage. Area basis uses an industry standard in-use parameter, whereas volume basis can link other life cycle stages to the manufacturing stage to construct a cradle-to-gate LCI or a LCA. The selection of unit in reference to the final product may change the results and needs to be considered when reporting LCI results and making comparisons.

Carbon stored in the flooring—1100 kg CO_2 equivalents—exceeds by 4% the amount required to offset fossil CO_2 emitted and offsets 66% of total CO_2 emissions during manufacturing.

A tradeoff exists between prefinished and unfinished engineered wood flooring. A large amount of electricity is consumed during the prefinishing unit process to control emissions during staining and coating of wood flooring. As a result, the environmental impact is significantly greater for prefinished engineered wood flooring than for unfinished engineered wood flooring. However, finishing the wood floor after installation in a residential or commercial building (an uncontrolled environment) may result in increased emissions released from the staining and coating process that would have been captured or destroyed on-site at the flooring plant.

Burning fuel for energy generates CO_2. Nearly all energy burned on-site for manufacturing prefinished engineered wood flooring comes from woody biomass. Burning biomass for energy does not contribute to increasing atmospheric CO_2 provided forests are regrowing and reabsorbing the emitted CO_2 on a sustainable basis. Increasing on-site wood fuel consumption would decrease fossil greenhouse gases but increase other gases, especially particulate emissions. Particulate matter can be captured prior to release with commercially available technology but not without increased costs.

ACKNOWLEDGMENTS

This project would not have been possible without the support of several key individuals and organizations. The authors especially thank Ed Korczak, past Executive Director and CEO, National Wood Flooring Association (NWFA), for critically needed financial support and promotion of this project. In addition, they thank the participating companies and individual mill respondents from the engineered wood flooring industry, NWFA members, for their time and effort in providing the primary data needed to make this project a success.

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