# A GATE-TO-GATE LIFE-CYCLE INVENTORY OF SOLID HARDWOOD FLOORING IN THE EASTERN US

*Steven S. Hubbard**

Graduate Research Assistant

*Scott A. Bowe*†

Associate Professor and Wood Products Specialist
Department of Forest and Wildlife Ecology
University of Wisconsin-Madison
120 Russell Laboratories
1630 Linden Drive
Madison, WI 53706-1598

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**Abstract.** Environmental impacts associated with building materials are under increasing scrutiny in the US. A gate-to-gate life-cycle inventory (LCI) of solid strip and solid plank hardwood flooring production was conducted in the eastern US for the reporting year 2006. Survey responses from hardwood flooring manufacturing facilities in this region accounted for nearly 28% of total US solid hardwood flooring production for that year. This study examined the materials, fuels, and energy required to produce solid hardwood flooring, coproducts, and the emissions to air, land, and water. SimaPro software was used to quantify the environmental impacts associated with the reported materials use and emissions. Impact data were allocated on their mass contribution to all product and coproduct production of 1.0 $m^3$ (oven-dry mass basis) of solid hardwood flooring. Carbon flow and transportation data are provided in addition to the LCI data. Results of this study are useful for creating a cradle-to-gate inventory when linked to LCIs for the hardwood forest resource and the production of solid hardwood lumber in the same region.

***Keywords:*** Hardwood flooring, life-cycle inventory, LCI, building material, carbon balance, environmental impact.

## INTRODUCTION

### Background

In response to growing concerns for the environment, there has recently been a fast-paced evolution of environmental certification and green building programs. The latter, green building, aims to reduce the environmental footprint of residential and commercial building construction through the selection of products and processes deemed energy-efficient and environmentally benign. Green-built structures are increasing and market share is forecasted to be 5% ($19 billion) of new residential starts by 2010 (MHC 2006). To aid program development and policymaking in such systems, scientific evaluation is needed for the collective impact of product alternatives to the environment and human health. Solid hardwood flooring is widely used in commercial and residential buildings. Through a gate-to-gate life-cycle inventory (LCI), this study provides baseline data for the accounting of the raw materials, energy, and emissions required to produce solid strip and solid plank hardwood flooring in the eastern US.

It is estimated that there are between 100 and 150 manufacturing facilities in the US with dedicated production of solid hardwood flooring (Locke 2006). Most domestic hardwood flooring production occurs in the eastern US because of the proximity of hardwood forests. Innovation, technology, and consumer preference have led to a diverse hardwood flooring product mix. Although no longer confined to traditional species, materials, or sizes, several generalizations

* Corresponding author: shubbard@wisc.edu
† SWST member

can be made. Solid hardwood flooring has three classifications: strip, plank, and parquet. Parquet flooring was not considered in this study. Strip flooring dominates overall production and is considered to have common face widths of 38, 57, or 83 mm. Plank flooring is classified by face widths of 76 – 203 mm. The predominant thickness for both flooring classifications is 19 mm. Random flooring lengths are popular in the US. Common domestic hardwood species used for solid flooring reported by manufacturing respondents were: red oak, white oak, sugar maple, red maple, ash, birch, walnut, cherry, beech, hickory, and pecan. Red oak was the dominant species used, representing nearly 70% of the market.

Using protocol guidelines established by the Consortium for Research on Renewable Industrial Materials (CORRIM) and the International Organization for Standardization (ISO), this LCI study serves as a benchmark for examining the environmental impact of producing solid hardwood flooring (CORRIM 2001; ISO 2006). It is intended to help a diverse group of stakeholders to make informed decisions about product selection and to provide insight about how the environmental footprint of this product might be reduced. Additionally, this LCI can be used in conjunction with parallel LCI studies for the hardwood forest resource and hardwood lumber production to develop a more extensive cradle-to-gate LCI.

## Study Scope

This study chronicled solid hardwood flooring manufacture for production mills located in the eastern US. The study region is the shaded portion shown in Fig 1 and included: Minnesota, Iowa, Missouri, Wisconsin, Illinois, New Jersey, Ohio, Indiana, Michigan, West Virginia, Pennsylvania, Maryland, Delaware, New York, Maine, Vermont, New Hampshire, Rhode Island, Massachusetts, Connecticut, Virginia, Kentucky, Arkansas, Louisiana, Mississippi, Alabama, Florida, Georgia, North Carolina, South Carolina,

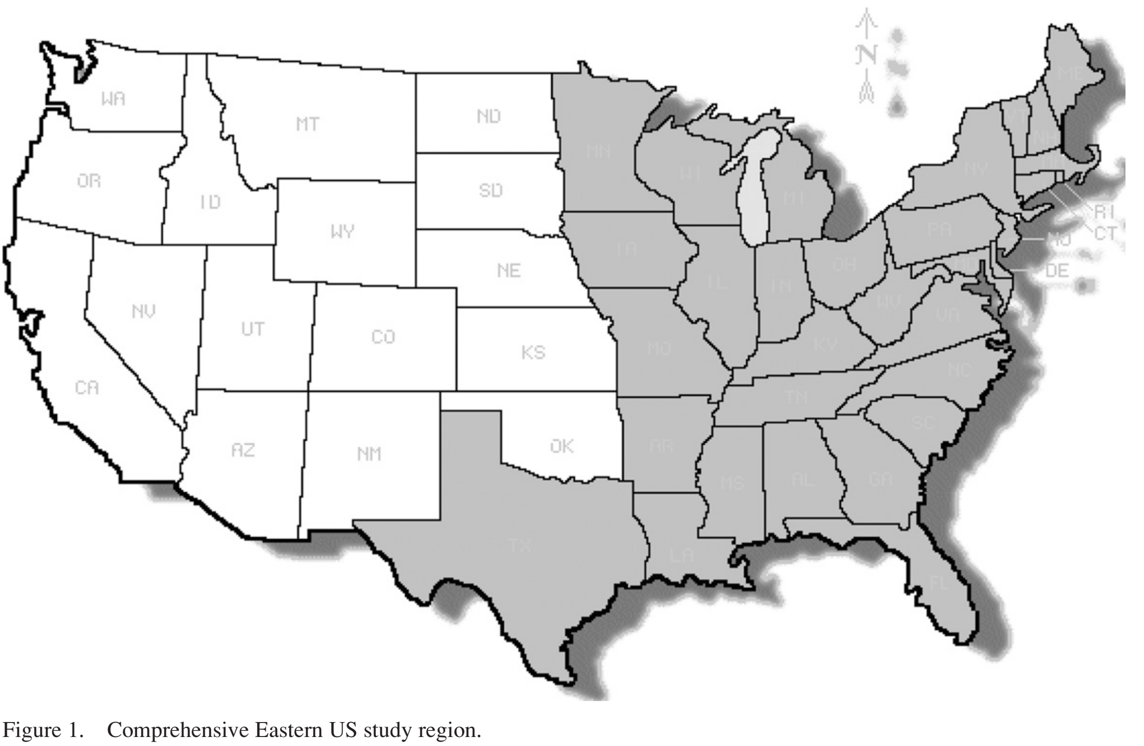


Figure 1. Comprehensive Eastern US study region.

Tennessee, and Texas. Total production of solid hardwood flooring in the US for 2006 was estimated at 45 $Mm^2$ (Wahlgren 2007); regional production totals were not found.

## Production Process Description

Hardwood flooring manufacture is accomplished through a series of unit processes. A unit process may be thought of as a machine center, a work cell, or a specific operational task that both requires and modifies a material input. The flooring LCI was modeled using a single-unit process approach that incorporated the key centers found in typical manufacturing. These processes are: receiving lumber (both green and dry), planing, ripping, trimming, side- and end-matching, molding, and packaging. Facility heat generation by on-site boilers and emission control devices is also considered an important process and is included in the analysis. Coproducts associated with the process include trimmings, edgings, planer shavings, wood flour, and sawdust. For the flooring to be stable in its service life, a final MC of 6 – 9% is desired. Although many flooring facilities purchase green lumber and kiln-dry on-site, data for this process were not collected in the survey questionnaires. Impacts associated with kiln-drying are included through secondary data for the hardwood lumber input provided in a model developed by Bergman and Bowe (2007a). Some mills add further value to their hardwood flooring by applying a prefinish. Mills in this study reported that prefinishing was accomplished at separate facilities and provided best guess responses for requested data. For these reasons, we omitted prefinishing and its impact.

## Functional Unit

The functional unit in this LCI was 1.0 $m^3$ of solid hardwood flooring made from the following species: red oak, white oak, sugar maple, red maple, ash, birch, walnut, cherry, beech, hickory, and pecan. In accordance with CORRIM and ISO protocols, all input and output data were allocated to this functional unit of product based on the mass (oven-dry basis) of products and coproducts (CORRIM 2001; ISO 2006).

## System Boundary

To account for materials and energy as well as the environmental impact, we defined two system boundaries for the gate-to-gate LCI (Fig 2). The cumulative system boundary (solid line box, Fig 2) represents the accounting for both on- and off-site materials, energy consumed, and associated emissions. Impacts associated with growing, harvesting, and transportation of logs were not included. The second system boundary (dashed line box, Fig 2) is the on-site boundary. This boundary considers the aforementioned accounting of materials, energy, and emissions found only at the flooring production facility. This second system boundary represents the processes for which primary data were collected from flooring manufacturers. Transportation of lumber from the sawmill to the flooring mill, production of grid electricity, and fuels not produced on-site are examples of off-site considerations.

## Data Collection and Assumptions

Between April and August 2007, primary data for 2006 were collected from flooring mills considered representative of the industry. Mills were surveyed using a self-administered questionnaire that was constructed using CORRIM and ISO 14044 standards and protocols (CORRIM 2001; ISO 2006). The survey was externally reviewed by members of CORRIM, scientists at the University of Wisconsin, and employees at the USDA Forest Products Laboratory. It was then pretested with a flooring manufacturer in the study region. The National Wood Flooring Association identified representative mills and provided detailed contact information for each. Eighteen questionnaires were mailed to nine companies. Three of the nine companies participated and ten surveys were returned and useable. Some of the companies had more than one production facility. In those cases, a questionnaire was requested for each

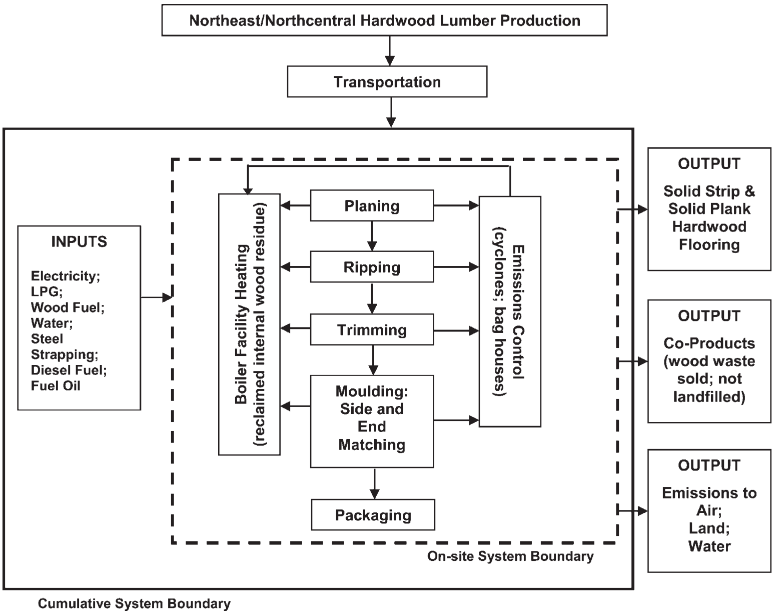


Figure 2. System boundaries for solid strip and solid plank hardwood flooring production.

facility. All participating companies were assured confidentiality. Mills surveyed reported a combined total production value of 12,425,488 $m^2$ of solid hardwood flooring. This represented nearly 28% of the total US hardwood flooring production for 2006. Data quality was considered very good for this study based on mill representativeness, peer review, and captured production.

Consistent with previous CORRIM studies (Milota et al 2005), survey data were weight-averaged across all mills by determining its production relative to the total production for mills in the survey. Missing or questionable data were addressed by follow-up correspondence with survey respondents; missing data that could not be resolved were omitted from averaging. Density values for wood species reported by flooring manufacturers were obtained from the National Hardwood Lumber Association (NHLA 2003), which was a concise tabulation of data acknowledged to be taken from the Wood Handbook: Wood as an Engineering Material (FPL 1999) and from the USDA Forest Service Hardwoods of North America (FPL 1995). A single density value for flooring and input lumber was derived by calculating the oven-dry weight of weight-averaged species input for reported flooring production. The calculated density value for flooring was 657 $kg/m^3$. Rough kiln-dry lumber input was reported in board feet and converted to cubic meters with the conversion factor 2.36 (Briggs 1994). Conversion to $m^3$ was done in a commercial spreadsheet based on actual reported thicknesses for each flooring width classification.

## Product Yields

Product yields observed in the survey showed how the input lumber was processed into products, coproducts, and waste. Production of 1.0 $m^3$ of solid hardwood flooring required 2.1 $m^3$ of input lumber, a recovery of 46%. The remaining 1.1 $m^3$ of input lumber was classified as wood residue, which was sold off-site or used on-site as hogged fuel for heat generation. Values were obtained by dividing the weight of wood in hardwood flooring by the total weight of input lumber and multiplying by 100%. Findings here are consistent with previous yield studies reported for this product (Hosterman 2000; Bond et al 2006). A wood mass balance was completed to account for all wood reported as inputs and outputs to flooring manufacture. To yield 657 $kg/m^3$ (oven-dry basis) of solid strip hardwood flooring and 762 $kg/m^3$ of wood residue, 1419 $kg/m^3$ of rough kiln-dry hardwood lumber was used. A difference of 0.6 $kg/m^3$ was observed between total recorded wood input and output, which was less than 1% of the total and considered excellent for a survey of this size.

## Transportation

Delivery of the hardwood lumber from sawmills to the flooring mills was by truck; no mills reported delivery by rail. The averaged one-way delivery distance was 283 km and mills reported that the trucks were empty on backhaul. Burdens associated with this transportation are included in the cumulative system boundary but are omitted from the on-site boundary analysis. Transportation data for packaging material were not reported and subsequently not included in the analysis.

## Model Structure

Consistent with previous CORRIM LCI, this study used SimaPro LCI software (Kline 2005; Milota et al 2005; Puettmann and Wilson 2005; Wilson and Dancer 2005a, 2005b; Wilson and Sakimoto 2005). SimaPro uses internationally recognized (ISO 2006) standards for environmental management and standardized LCI formats to record and analyze the model data (PRé Consultants 2006).

Data collected for hardwood flooring gate-to-gate LCI were processed using SimaPro version 7.0 (PRé Consultants 2006). This version has a built-in database by Franklin Associates containing energy and materials characteristics representative of those found in North America (FAL 2001). To more accurately account for all input and output flows, this inventory was modeled using a single box approach. In effect, the seven unit processes, planing, ripping, trimming, side- and end-matching, packaging, boiler energy generation, and emissions control, are aggregated. The advantage of this approach was that hardships encountered in allocating inputs and outputs to a given machine center (largely best guesses by survey respondents) were avoided. Data that were collected in the survey and input to the model software appear in Table 1.

# LIFE-CYCLE INVENTORY RESULTS

## Energy Sources

Energy required to produce solid hardwood flooring comes from several sources. Purchased electricity was used to operate conveyance and pneumatic equipment as well as saws, planers, molders (matchers), and emission control devices. Thermal energy was used to operate kilns and for facility heating. For the on-site system boundary in this study, thermal energy was confined to facility heating. Energy use associated with kiln drying the hardwood lumber was accounted for in the cumulative system boundary through a hardwood lumber production input

Table 1. *Survey data input to the hardwood flooring model by type and quantity required to produce 1.0 $m^3$ of solid hardwood flooring.*

| Inputs to the model | Quantity in SI units per 1.0 $m^3$ |
|---|---|
| Materials | |
| Rough kiln-dry hardwood lumber | 1419 kg |
| Water from ground | 6.21 L |
| Steel strapping, cold rolled | 0.15 kg |
| Fuels | |
| Purchased electricity | 48.4 MJ |
| Wood hogged fuel produced on-site | 29.1 kg |
| Natural gas | 0.89 $m^3$ |
| Fuel oil No. 6 | 0.01 L |
| Propane | 0.12 L |
| Gasoline | 0.02 L |
| Off-road diesel | 0.27 L |
| Emissions | |
| Particulates, unspecified | 0.01 kg |
| Particulates less than10 μm | 0.007 kg |
| Discharged to sewer or surface | 0.01 L |
| Fly ash | 1.32 kg |

Weight averaged data from 10 mills; all data allocated by mass to production of 1.0 $m^3$ hardwood flooring (oven-dry basis 657 $kg/m^3$); values in the table are for the on-site boundary only.

(Bergman and Bowe 2007a). With the exception of one mill, all used industrial boilers to combust wood residue (hogged fuel) generated on-site to provide thermal energy. On-site transportation by forklifts, trucks, and carriers relied on gasoline, diesel fuel, and liquid propane gas.

## Electricity Use

Purchased electricity (off-site electrical grid) required to operate the machine centers was reported by 7 of the 10 mills. For the on-site system boundary to produce 1.0 $m^3$ of solid hardwood flooring, 48.4 MJ of electricity was consumed. Mills were unable to provide a percentage allocation of electrical use per unit process. By comparison, electrical use for the cumulative system boundary that included hardwood lumber production was 656 MJ. This jump in electrical use illustrates the energy intensity of kiln-drying lumber.

## Thermal Energy

Wood residue produced on-site was used to fuel on-site boilers. Mills in this study reported meeting all thermal energy demands with wood hogged fuel produced on-site. Thermal energy associated with the production of 1.0 $m^3$ of flooring produced on-site for facility heating used 29 kg/$m^3$ of wood residue (oven-dry basis).

## Cumulative Energy Use

Electricity was the most prevalent form of energy used in the system boundary for hardwood flooring manufacture. Coal used to produce this electricity was the largest off-site energy source. Thermal energy produced by combusting wood in on-site boilers was second followed by the fossil fuels natural gas and No. 6 fuel oil. The Eastern region produces electricity with a variety of fuel sources. The average composition of off-site electrical generation was determined for this region by averaging values given for the Northeast-North Central and Southeastern regions (USDOE 2006). Table 2 shows the breakdown by fuel source used to determine Eastern region electricity values. Major fuel sources used to produce the purchased electricity were coal, nuclear, petroleum, natural gas, and hydroelectric. Table 2 includes electrical power requirements for both the on-site flooring system boundary and with addition of the Northeast-North Central lumber production (Bergman and Bowe 2007b).

## Emissions

Table 3 displays the cumulative LCI results for raw materials consumed in the production of 1.0 $m^3$ of solid hardwood flooring; allocated emissions to air and water are shown in Tables 4 and 5, respectively. Values for both the cumulative system boundary (on-site and off-site) and the on-site system boundary are presented. Sources for these emissions are from fuel production, fuel use, and processing the input lumber. The resulting emissions to land occur as solid waste and fly ash. Considering the cumulative system boundary, these values are 3.92E+0 and 6.11E-01 kg/$m^3$ for solid waste and fly ash, respectively.

## Carbon Balance

Carbon emissions are under increasing scrutiny worldwide. A carbon balance for the production of hardwood flooring was performed. For the on-site hardwood flooring inventory, SimaPro gave per unit (1 $m^3$) flooring carbon emission values of 28.2 kg for biogenic $CO_2$ and 5.73 kg

Table 2. *Electric power requirements to produce 1.0 $m^3$ of solid hardwood flooring; data are allocated and cumulative.*

| Fuel source | Percentage of total 2006 electricity production | On-site hardwood flooring (MJ/$m^3$) | Cumulative (MJ/$m^3$) |
|---|---|---|---|
| Coal | 51.8 | 25.1 | 340 |
| Petroleum | 3.9 | 1.89 | 25.6 |
| Natural gas | 16.4 | 7.95 | 107 |
| Hydro | 2.3 | 1.11 | 15.09 |
| Nuclear | 22.8 | 11.05 | 149 |
| Other renewables | 2.8 | 1.35 | 18.3 |
| Total | 100 | 48.4 | 656 |

Note: Totals are subject to rounding error. Reported value for total Northeast-North Central electricity was 608 MJ per 1.0 $m^3$ (Bergman and Bowe 2007b).

Table 3. *Life-cycle inventory results for raw materials consumed in the production of 1.0 $m^3$ of solid hardwood flooring; data are allocated and cumulative.*

| Substance | $kg/m^3$ |
|---|---|
| Coal[a] | 8.82E+02 MJ |
| Energy, hydro[a] | 1.10E+01 MJ |
| Energy (unspecified)[a] | 8.00E+00 MJ |
| Natural gas[a] | 1.07E+03 MJ |
| Hardwood bark[b] | 9.50E+01 |
| Logs (unspecified)[b] | 1.66E+00 |
| Limestone | 5.81E+00 |
| Crude oil[a] | 8.08E+02 MJ |
| Oxygen, in air | 6.83E-03 |
| Scrap, external | 2.71E-02 |
| Uranium | 5.69E+01 MJ |
| Well water | 3.03E+00 |
| Iron ore | 8.25E-02 |
| Wood and wood waste | 1.68E+03 MJ |

Values in the table are for cumulative site boundary; includes transportation.

[a] Per CORRIM protocol, energy values are reported using their higher heating values (HHVs) in MJ/kg. HHVs are: oven-dry wood 20.9, coal 26.2, distillate fuel oil 45.5, liquid propane gas 54.0, natural gas 54.4, gasoline 54.4, and uranium 381,000.

[b] Northeast-North Central hardwood lumber module (Bergman and Bowe 2007a).

for fossil fuel $CO_2$. If impacts associated with lumber production from the cumulative system boundary are taken into account, these values rise to 526 and 170 kg for biogenic and fossil fuel $CO_2$, respectively. Biogenic $CO_2$ emissions from the combustion of wood are considered impact-neutral (EPA 1999). The carbon balance for the flow of wood in the production of solid strip and solid plank hardwood flooring appears in Table 6. Carbon from lumber, solid wood flooring, and wood residue was tracked; carbon flows associated with hardwood lumber production were not included. The amount of carbon in wood was determined by averaging regional values for the amount of carbon found in hardwoods reported by Skog and Nicholson (1998). The regions included North Central, Northeast, South Central, and Southeast. The average hardwood factor used was 305 $kg/m^3$ of carbon. Input carbon was 305 $kg/m^3$ and output carbon totaled 313 $kg/m^3$. Three percent of the carbon

Table 4. *Emissions to air for cumulative (on-site and off-site) impact and gate-to-gate (on-site impact) for the production of 1.0 $m^3$ of solid hardwood flooring; data are allocated.*

| Substance | Cumulative ($kg/m^3$) | On-site ($kg/m^3$) | Substance | Cumulative ($kg/m^3$) | On-site ($kg/m^3$) |
|---|---|---|---|---|---|
| Acetaldehyde | 7.12E-04 | 5.91E-08 | Kerosene | 3.26E-05 | 1.69E-06 |
| Acrolein | 1.21E-06 | 2.08E-05 | Lead | 3.45E-04 | 1.74E-05 |
| Aldehydes | 7.68E-03 | 1.94E-05 | Manganese | 2.26E-03 | 1.21E-04 |
| Ammonia | 2.86E-04 | 2.63E-08 | Mercury | 2.55E-06 | 1.10E-07 |
| Antimony | 1.05E-06 | 1.30E-06 | Metals (unspecified) | 2.05E-05 | 7.73E-07 |
| Arsenic | 2.56E-05 | 5.90E-05 | Methane | 2.86E-01 | 1.26E-02 |
| Barium | 1.10E-03 | 5.53E-08 | Methane, HCC-30 | 4.81E-06 | 2.31E-07 |
| Benzene | 8.55E-04 | 1.46E-08 | Methane (CFC) | 2.38E-06 | 6.46E-08 |
| Beryllium | 4.01E-07 | 1.61E-08 | Nitrodimethylamine | 2.55E-07 | 1.25E-08 |
| Cadmium | 2.20E-06 | 5.91E-08 | Naphthalene | 5.69E-04 | 4.65E-09 |
| $CO_2$ (biogenic) | 5.26E+02 | 2.82E+01 | Nickel | 1.69E-04 | 7.78E-06 |
| $CO_2$ (fossil) | 1.70E+02 | 5.73E+00 | Nitrogen oxides | 1.34E+00 | 4.68E-02 |
| CO | 4.01E+00 | 1.95E-01 | VOC (nonmethane) | 3.54E-01 | 8.53E-03 |
| Chlorine | 1.96E-03 | 1.05E-04 | Organic (unspecified) | 1.76E-01 | 4.49E-05 |
| Chromium | 1.69E-05 | 7.83E-07 | Particulates | 1.35E+00 | 5.00E-03 |
| Cobalt | 2.59E-06 | 5.49E-08 | Particulates, less than 10 μm | 1.16E-01 | 9.59E-03 |
| Copper | 1.04E-09 | 1.04E-09 | Particulate (unspecified) | 9.39E-02 | 1.46E-07 |
| Dinitrogen | 6.93E-04 | 3.30E-05 | Phenol | 9.49E-03 | 1.05E-02 |
| Dioxins | 6.39E-12 | 3.12E-13 | Potassium | 1.96E-01 | 1.69E-06 |
| Ethene, tetrachloro | 1.16E-06 | 5.59E-08 | Radioactive unspecified | 1.30E+06 | 7.41E+04 Bq |
| Ethene, trichloro | 1.14E-06 | 5.58E-08 | Selenium | 9.10E-06 | 4.19E-07 |
| Formaldehyde | 5.33E-03 | 1.13E-04 | Sodium | 4.51E-03 | 2.42E-04 |
| Hydrogen chloride | 6.05E-03 | 2.96E-04 | Sulfur oxides | 1.28E+00 | 4.86E-02 |
| Hydrogen fluoride | 8.40E-04 | 4.11E-05 | VOCs | 1.40E+00 | N/R |
| Iron | 1.10E-03 | 5.90E-05 | Zinc | 1.10E-03 | 5.91E-05 |

VOCs, volatile organic compounds.

Table 5. *Emissions to water for cumulative (on-site and off-site) impact and gate-to-gate (on-site impact) for the production of 1.0 $m^3$ of solid hardwood flooring; data are allocated.*

| Substance | Cumulative (kg/$m^3$) | On-site (kg/$m^3$) |
|---|---|---|
| Acidity (unspecified) | 1.88E-08 | 1.76E-10 |
| Acids (unspecified) | 1.38E-08 | 1.38E-08 |
| Ammonia | 9.80E-05 | 3.72E-06 |
| Biochemical oxygen demand | 1.23E-03 | 3.85E-05 |
| Boron | 3.22E-03 | 1.46E-04 |
| Cadmium ion | 4.73E-05 | 1.71E-06 |
| Calcium ion | 2.80E-05 | 1.46E-06 |
| Chloride | 4.76E-02 | 1.73E-03 |
| Chromate | 1.57E-06 | 9.68E-09 |
| Chromium | 4.73E-05 | 1.71E-06 |
| Chemical oxygen demand | 1.56E-02 | 5.35E-04 |
| Cyanide | 1.74E-07 | 1.06E-07 |
| Fluoride | 1.30E-04 | 6.75E-06 |
| Iron | 4.62E-03 | 2.36E-04 |
| Lead | 3.38E-08 | 5.01E-10 |
| Manganese | 2.64E-03 | 1.32E-04 |
| Mercury | 3.71E-09 | 1.34E-10 |
| Metal ions (unspecified) | 4.03E-04 | 3.77E-06 |
| Nitrate | 1.22E-05 | 6.36E-07 |
| Oils (unspecified) | 1.89E-02 | 6.66E-04 |
| Organic (unspecified) | 3.59E-03 | 1.36E-04 |
| Phenol | 1.34E-06 | 5.84E-08 |
| Phosphate | 4.03E-04 | 1.83E-05 |
| Sodium ion | 5.15E-05 | 2.68E-06 |
| Solved solids | 1.06E+00 | 3.78E-02 |
| Sulfate | 5.32E-02 | 2.18E-03 |
| Sulfuric acid | 8.05E-04 | 3.66E-05 |
| Suspended solids | 7.04E-02 | 3.24E-03 |
| Water | 5.91E-03 | 5.91E-03 |
| Zinc ion | 1.67E-05 | 5.93E-07 |

Table 6. *Wood-based carbon flow for on-site hardwood flooring production.*

| Substance | Carbon content (kg/$m^3$) |
|---|---|
| Input | |
| Rough dry hardwood lumber | 305 |
| Sum carbon in | 305 |
| Output | |
| Solid strip/plank hardwood flooring | 145 |
| Coproducts[a] | 159 |
| Air emissions | 9.36 |
| Solid emissions | — |
| Sum carbon out | 313 |

[a] Includes wood residue: sawdust, planer shavings, edging strips, trimmings, wood flour, and wood fuel combusted on-site.

was unaccounted for. The inherent variability of the survey data, coupled with limitations in input and output measuring accuracy, accounts for the discrepancy.

## DISCUSSION

Care is needed in interpreting the results of LCI. In addition, product comparisons across alternative or substitute products are meaningful only when the same methods and system boundaries are used to derive the results. The repercussions of comparing "apples to oranges" could lead to significantly flawed conclusions.

It was clear that boundary selection had a large influence on the observed results. In this study, the manufacturing requirements to produce the kiln-dry lumber input for flooring production carries the majority of environmental and fuel use burden. Even so, these associated impacts are consistent with other studies of this type that have consistently shown wood product manufacture to be less energy-intensive compared with that of wood substitutes (Lippke et al 2004).

Considering the hardwood flooring production process in isolation from the additive effects of lumber production, several observations can be made. First, the manufacturing process to produce this product is relatively straightforward. Not surprisingly, therefore, the environmental burdens on-site are confined to select sources. The majority of required energy within the on-site system boundary was in the form of purchased electricity to run conveyance, sawing, and emission control equipment. Coal represents nearly 52% of the regional fuel input used to generate this purchased electricity in the Eastern region. The associated carbon from coal is fossil (anthropogenic) and not considered biogenic. Mining extraction and the associated processes required to produce steel strapping material used in packaging the flooring is another consideration because the raw material inputs are not considered renewable resources.

Hardwood flooring is dependent on hardwood lumber, which carries its own environmental footprint and is unreasonable to be ignored. In terms of environmental impact, kiln-drying lumber was arguably the most intensive process; however, it was not included in the on-site boundary. This was because the hardwood lumber module developed by Bergman and Bowe (2007a) was the logical input to extend the gate-to-gate LCI and had already included the kiln-drying process for the same species. Because hardwood lumber used for flooring must be dried to final moisture contents of 6 – 9% for stability in service, the associated burdens of kiln-drying are important considerations. The cumulative boundary was therefore considered. The energy required (thermal and electrical) during the hardwood drying process is significant. It has been estimated that of the total amount of energy required to produce hardwood lumber, approximately 75% is devoted to drying operations (Comstock 1975). In their study of hardwood lumber production, Bergman and Bowe (2007b) found that electrical energy used in drying consumed 152 $MJ/m^3$. Thus, considering the cumulative boundary for flooring production, nearly 25% of the total electricity required was for drying wood. A second consideration in the drying process is the subsequent release of volatile organic compounds (VOCs), which are considered carbon compounds capable of photochemical reactions in the earth's atmosphere. Of these, $CO_2$ is considered the most significant contributor to global warming. Care must be taken not to release VOCs into the environment because they are damaging to groundwater, soil, and air. It is important to recognize that the majority of thermal energy requirements for kiln operation can be met through the use of wood residues generated on-site. This means that most mills are able to successfully use significant portions of their wood waste streams, keeping woody biomass out of landfills.

Of importance in evaluating the environmental footprint of hardwood flooring is the renewable nature of the hardwood resource. Sustainable forest management aims to provide a consistent supply of timber, but also provide a habitat for wildlife and other nontimber forest uses. The same cannot be said for all material inputs used to derive substitute or alternative products (Jönsson et al 1997). Consider the environmental tradeoffs associated with various land use and resource extraction scenarios. A case can be made for the benefits of larger mixed-hardwood forests than for mining or single crop systems (Wilson 2006). The latter is often characterized by intensive material and energy input as well as lower species diversity.

Additional considerations are product service life and disposal. Hardwood flooring has advantages over other floor coverings such as vinyl and carpet if one considers service life. It is not unreasonable to expect that, properly cared for, solid hardwood flooring can last 35 – 75+ yr. By comparison, one estimate puts the service life of vinyl at about 18 yr (NIST 2007). A shorter service life means that the product will need to be replaced (more production and associated burdens) more frequently. The disposal of these products is also important to consider. Wood flooring stores carbon throughout its service life. After its useful service life, wood can be recycled or used for fuel.

## CONCLUSIONS

This study modeled a gate-to-gate LCI for solid strip and solid plank hardwood flooring production in the Eastern US. Ten manufacturing facilities with dedicated production of this flooring produced nearly 28% of total domestic flooring for 2006. Using methodology by ISO and CORRIM, primary data were collected, weight-averaged, and modeled using SimaPro software version 7.0 (CORRIM 2001; ISO 2006; PRé Consultants 2006). Secondary data were obtained from the US Department of Energy, CORRIM, and a recently completed hardwood lumber production module (USDOE 2006; Bergman and Bowe 2007a). Although not included in the on-site flooring production boundary, energy and emissions associated with bringing the needed hardwood lumber to a final dry MC of 6 – 9% represented the greatest environmental impact. The impacts from drying can be categorized as the creation of VOCs and thermal and electrical energy requirements to operate the kilns. Biogenic $CO_2$ resulting from the inventory was much greater than fossil-derived. This was viewed as beneficial because biomass $CO_2$ is regarded in many scientific circles to be environmentally neutral (EPA 1999). LCI data such as those presented in this study can be used to contribute to broader scoped life-cycle assessments and modular assembly scenarios. If the methodologies used to generate product life-cycle studies for substitute or alternative floor coverings do not use matching methods, it is inappropriate to make product comparisons. The data contained in this study support other studies reviewed in the literature that have concluded wood flooring is relatively environmentally benign across many of its physical attributes (Jönsson et al 1997; Nebel et al 2006). This study did not examine the burdens associated with coatings or finishing products; future studies should consider doing so.

As a means of improving environmental performance based on the inventory results in this study, the following observations were made:

- Although the use of woody biomass to generate on-site manufacturing energy produces particulate emissions, the benefits are large in using a carbon-neutral fuel source as well as the reduced costs for fossil-derived fuels and disposal. Mills can benefit by capturing wood residue for use as value-added furnish on- and off-site.
- Kiln-drying is a necessary process to produce stable hardwood flooring. Because kiln-drying is energy-intensive, continued innovation and use of air-drying methods represents potentially large energy savings. Because of discolorations associated with fungal and enzymatic activity, and added inventory, this may not be practical.
- Electrical energy used to run rip and chop saws as well as other machine centers should be evaluated mill by mill. Replacing aging equipment and outdated technology with newer optimized counterparts has the potential to increase efficiency and yields and lower energy inputs. Similarly, implementing a regular check and maintenance schedule for all equipment represents a strategy that can reduce inefficiencies. Mills need to do cost-to-benefit analysis for such changes.
- Wood is a unique and renewable raw material. Flooring made from wood stores carbon during its service life. The unique process of carbon sequestration in trees makes biomass-derived $CO_2$ a carbon-neutral substance. At the end of its service in flooring, wood may be reused or used for fuel.

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