LIFE-CYCLE INVENTORY OF MEDIUM DENSITY FIBERBOARD IN TERMS OF RESOURCES, EMISSIONS, ENERGY AND CARBON

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Abstract. Life-cycle inventory (LCI) data are needed to scientifically document the environmental performance of materials for applications as governed by the many new green building standards, purchasing guidelines, and energy and climate change policy issues. This study develops the LCI data for medium-density fiberboard (MDF), a composite wood panel product comprised of wood fibers, urea–formaldehyde resin, wax, and other additives. Data are given for both on-site (MDF manufacture) and cradle-to-product gate (from the MDF upstream to in-ground resources) that includes those environmental impacts to produce and deliver input fuels, electricity, water, wood residue, resin, wax, and scavenger. LCI output data are given for raw materials use and emissions to air, water, and land. Data are also presented on embodied energy, carbon flux, store, and footprint. MDF has favorable characteristics in terms of energy use and carbon store. Of significance is the large component of embodied energy from wood fuel use, a renewable resource, and its small carbon footprint that lessens its impact on climate change.

Keywords: Environmental performance, MDF, wood products, life-cycle inventory, LCI, CORRIM, embodied energy, carbon store, carbon footprint.

INTRODUCTION

The objective of this study was to develop high-quality data on the environmental performance of producing medium-density fiberboard (MDF). The data form the foundation of a scientific assessment that can be used to provide useful information to meet the need by consumers and regulators, promote MDF as a green product, and provide a benchmark for continued improvement of its environmental performance and sustainability.

MDF is produced by consolidating wood fibers under heat and pressure that have been mixed with resin, wax, and other additives to form a uniform, dense panel product that is sawn to size and sanded on both sides. The wood fibers are processed from industrial wood residues such as shavings, sawdust, plywood trim, and chips and can be from chips from low-valued logs or urban wood waste—all sustainable materials. Generally, production facilities are located in regions of the US that are producers of primary wood products such as lumber and plywood to draw on their coproduct resources, but can also be located in regions accessible to a low-valued log supply. In 2004, the US industry produced 3,091,848 m^3 of MDF (CPA 2005).[1]

To establish the environmental performance of MDF, a life-cycle inventory (LCI) was done that consists of an accounting of all inputs and outputs of a product from its resources in the ground through production—referred to as a cradle-to-product gate study. The data can be used to establish the performance of MDF for many green type standards, guidelines, and

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[1]Production in the US is traditionally measured on 1000 square foot (MSF) 3/4-in-thickness basis and is now also given in SI units as m^3 with 1.0 MSF equivalent to 1.7698 m^3.

policies. Issues in which the data can be used include sustainability, global warming, climate change, carbon storage, carbon trading and caps, carbon taxes, biofuel use, green purchasing, and green building. The data can also be used to establish the performance of MDF in comparison with other materials by conducting life-cycle assessment (LCA) studies with output measures in terms of impact on human health, environment, and resource use.

MDF is a nonstructural panel product developed in the 1970s to use industrial wood residue from the production of primary wood products such as softwood lumber and plywood. These wood residues were previously burned or sent to a landfill to dispose of them as waste material. The process can also use logs and urban wood waste as a resource when the economics are favorable. Over the years, MDF has evolved into a highly engineered product designed to meet specific end-use requirements. MDF is an industrial-type panel product used as substrate for making household and office furniture, kitchen and bath cabinets, store fixtures, moulding, and door components.

MDF is produced to the material properties listed in the American National Standard ANSI A208.2-2009 (ANSI 2009) and can be made in a variety of panel sizes and thicknesses with most products in the 3- to 32-mm-thickness range.

PROCEDURE

The scope of this study was to document the LCI of manufacturing MDF panels in the US based on industrial wood residues as a resource. The study covers all environmental impacts from in-ground resources of wood, fuels, electricity, resin, wax, and scavengers through manufacture of MDF, documenting all input of materials, fuel, and electricity and all outputs of product, co-product, and emissions to air, water, and land. This is referred to as a cradle-to-product gate inventory (Fig 1). The LCI study was conducted

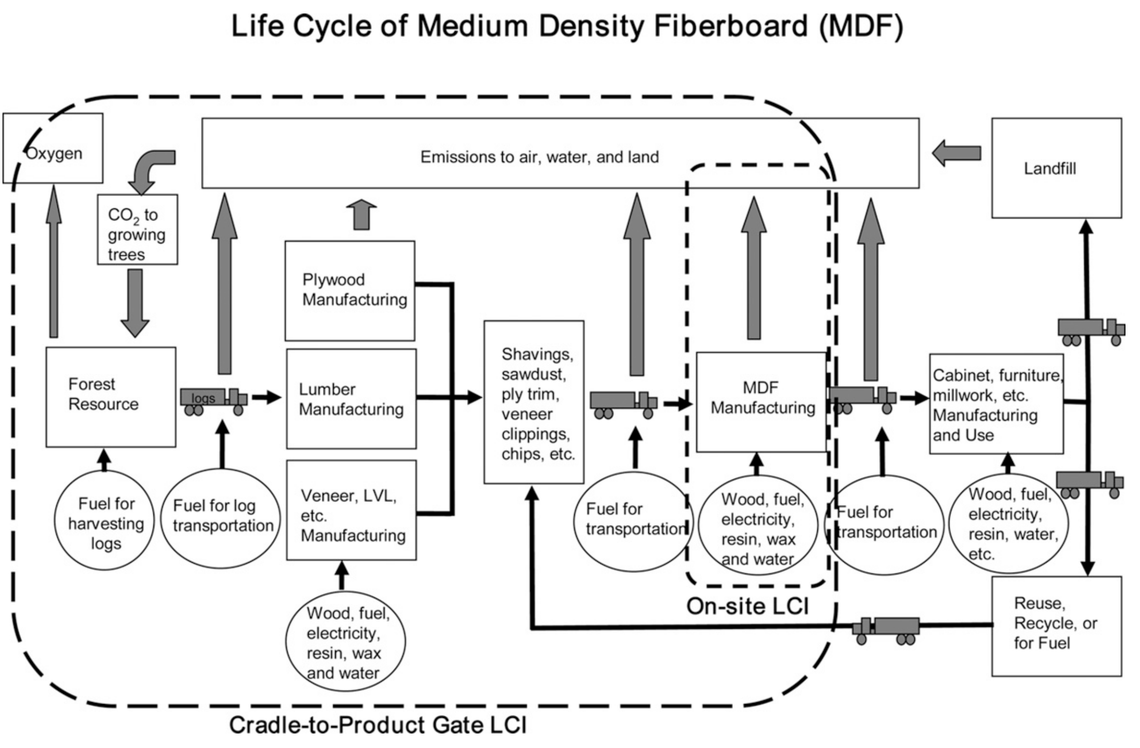

Figure 1. The life cycle of medium-density fiberboard (MDF) and its cradle-to-product gate life-cycle inventory system.

in accordance with the Consortium for Research on Renewable Industrial Materials (CORRIM) guidelines (CORRIM 2001) and ISO 14040 and 14044 protocol (ISO 2006a, 2006b).

Primary data were collected for MDF manufacture by conducting a survey questionnaire of the industry (for a copy of the survey form, see Wilson (2008)). The LCI data for the input wood residues were from data and analyses done in earlier CORRIM studies for the production of residues as coproducts from plywood and lumber manufacture (Milota et al 2005; Wilson and Sakimoto 2005). Also included from earlier CORRIM studies are the LCI of the forest resources, harvesting, and delivery impacts (Johnson et al 2005) as well as LCI data for production of urea–formaldehyde (UF) resin (Wilson 2009, 2010). Supplemental secondary data were obtained for impacts associated with the manufacture, delivery, and consumption of electricity and all fuels (FAL 2004; PRé Consultants 2007; USDOE 2007). Resin-associated chemicals of wax and urea scavenger (Ecoinvent 2007) were adjusted to US energy and electricity values using the FAL database where appropriate.

The survey of MDF production collected data from four mills that produced 833,221 m^3 in 2004, representing 28% of total production in the US. Thin MDF, a subgroup of MDF product of approximately 3- to 8-mm thickness, with about 13% of total US production, was not included in this study but would have relatively similar results.

SURVEY DATA ANALYSIS

The survey data from the MDF mills were analyzed for quality by assessing for outliers and conducting mass and energy balances. The data for all wood inputs and outputs are given as oven-dry, whereas chemical inputs of resin, wax, and scavenger are given as 100% solids. The data for each MDF mill were converted to a unit of production basis of 1.0 m^3 to make the comparison. Any data outliers were resolved by contacting the appropriate mill personnel. A mass balance considering all inputs materials of wood, resin, wax, and scavenger and all outputs of product and emissions had a difference of 0.3% that is well within the maximum 5% balance requirement of the CORRIM protocol. Energy balances were done to determine the expected energy use to remove the desired amount of water from the wood fibers during processing. The average MC of wood material coming into the mill was 39% on an oven-dry weight basis and the targeted MC for the dried material with resin applied was 7 – 9%. Considering the content of the fuels and the amount of moisture removed, the energy use for drying per kg of water removed was 6.01 MJ based on the higher heating value (HHV) of the various fuels. The energy use was found to be as expected. The data for the mills were then weight-averaged based on the production of each mill and the total production. Only weight-averaged data are presented in this study. The weight-averaged mill produced 208,305 m^3 annually of MDF at an average density of 741 kg/m^3 oven-dry.

MANUFACTURING PROCESS

The MDF manufacturing process is highly automated, process-controlled, and fairly linear (Fig 2). The process consists of the following steps:

- ***Sort and store:*** Wood residue is delivered to the mill normally by truck; the residue consists of shavings, sawdust, plywood trim, and chips of various moisture contents; the residue is stored under cover; the MC of the residue can range 10 – 100% on an oven-dry weight basis.
- ***Digesting:*** The wood residue is placed in a pressurized vessel (digester) to cook the wood in preparation for refining into fibers. The wood is cooked with steam at pressure to soften the lignin-binding material between its fibers.
- ***Refining:*** The heated wood residue is then refined, a process of mechanically reducing it into fibers by shearing the wood between two rotating metal disks that separate the fibers at the lignin binder; this process is usually accomplished with the use of a pressurized disk refiner.

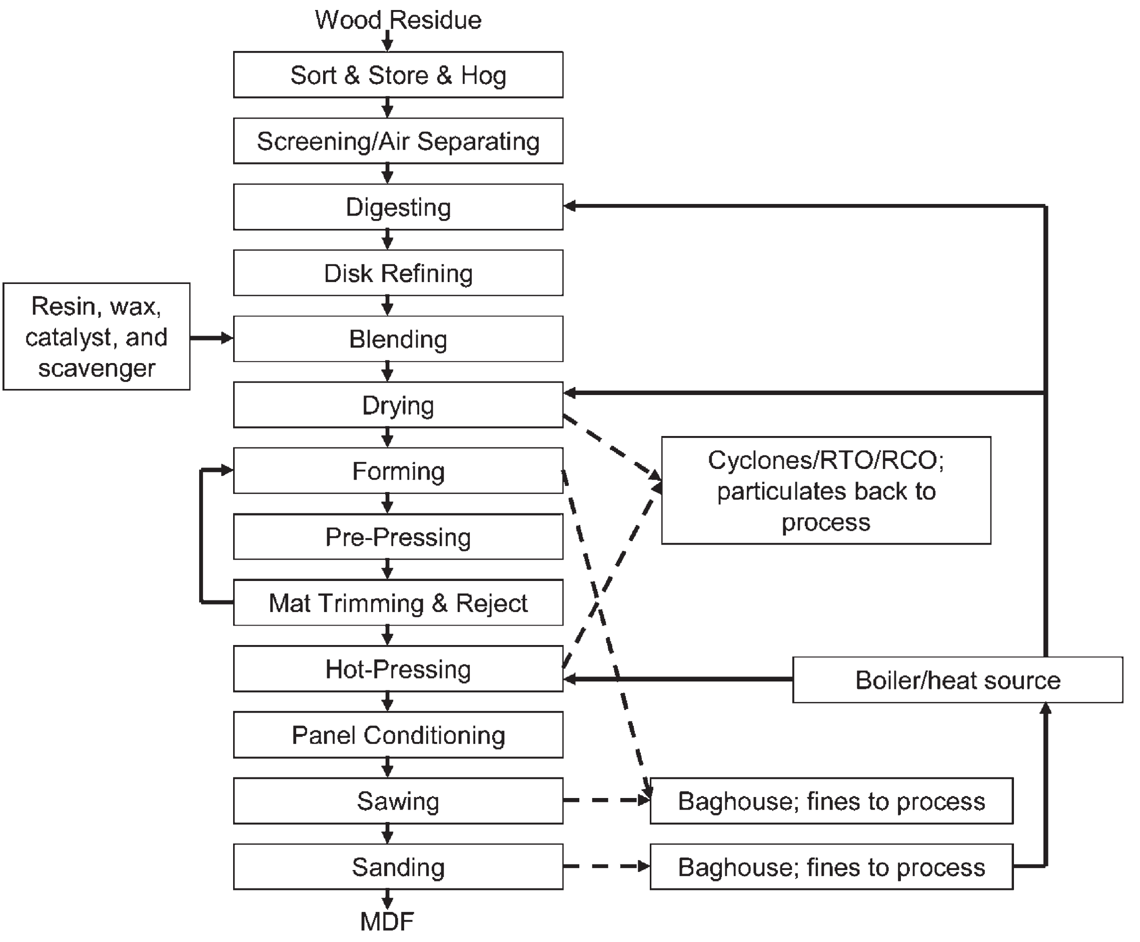

Figure 2. On-site process flow for the production of medium-density fiberboard.

- ***Blending:*** This is a process whereby resin, wax, and scavenger are distributed onto the fibers. Friction and contact between fibers may help to distribute the resin. The resin most used is UF; however, some products are made with either melamine–UF (MUF) or polymeric isocyanate (pMDI) resins for those products in which greater moisture resistance is desired. The resin and other additives can be applied to the fiber in either the refiner, coming out of the refiner in the blow line, or in the flash-tube dryer before forming.
- ***Drying:*** The particles are sent through dryers, normally flash-tube dryers consisting of long tubes; heated air is used to both dry and transport the fibers the length of the tube. The fibers enter the dryer at somewhat higher MCs than the 39% average residue entering the mill because of steam treating in the digester and are dried to a targeted MC of about 7 – 9% with resin applied. The dryers are normally direct-fired with natural gas, although some dryers use sander dust from a later process step. Heat sources based on wood fuel can also be used. As wood dries at elevated air temperatures of up to 260°C in the dryers, particulates and air emissions of volatile organic compounds (VOCs) and hazardous air pollutants (HAPs) are released.
- ***Forming:*** The blended fibers are distributed into a flat mat usually in multiple layers of three or five consisting of face and core layers. The

distribution of fibers, their moisture, and resin content can be controlled for the face and core layers to obtain the desired panel properties.

- ***Hot pressing:*** The formed mats are pre-pressed to reduce their thickness and provide mat integrity and are then conveyed into large presses. Most are stack presses of multiple openings in which all openings close simultaneously. Presses operate at about 170°C and with sufficient time to cure the resin and at a pressure of about 5.2 MPa to consolidate the mat to a desired density of 500 – 800 kg/m^3, thereby controlling the physical properties of the panel. As a result of the elevated temperature and resin curing, particulates and air emissions of VOCs, HAPs, and resin-related emissions are generated. Hot presses are heated with steam or hot oil.
- ***Conditioning:*** Hot panels are placed on an air-cooling wheel to enable the temperature of the panels to drop below a level at which the UF resin could start to break down with time and emit formaldehyde gas. Limited amounts of air emissions occur at this point.
- ***Sanding:*** Panels are sanded on both major surfaces to targeted thickness and smoothness. Sander dust coming off this process can either be recycled back into the process before blending or used as fuel for the dryers.
- ***Sawing:*** Relatively large panels are sawn to dimensions of panel width and length. Panel trim is hammermilled into particles and sent back into the process.

The panels are then stacked and prepared for shipping. Other important processes not included in this flow process but should also be mentioned are the boiler and its combustion of fuel to generate steam for process heat and emission control devices such as baghouses, cyclones, biofilters (BFs), regenerative thermal oxidizers (RTOs), and regenerative catalytic oxidizers (RCOs). Only one of the four mills used a combination of cyclones and RCO/RTO devices to reduce particulate, VOC, and HAP emission levels. Implementation of the Plywood and Composite Wood Products Maximum Achievable Control Technology (PCWP MACT) rule (USEPA 2004) necessitates that all MDF plants that cannot meet its emissions averaging, work-practice standards, or production-based limits must have some type of emission control system installed to meet regulations. This will result in a lowering of average HAP emissions and increased use of natural gas and/or electricity for their operation and in turn increased emissions related to the combustion of fossil fuels.

Functional Unit

For this study, material flows, fuel and electricity use, and emissions data are normalized to a per-production unit volume basis of MDF of 1.0 m^3—the functional unit—of finished MDF ready to ship. For those LCI practitioners that conduct studies on a mass basis, 1.0 m^3 of MDF weighs 741 kg oven-dry; therefore, dividing the data in this study by their volume weight will give all flows, materials, and emissions on a per 1.0 kg basis.

Life-Cycle Inventory Modeling

The environmental impact analysis was done using SimaPro 7.1 software and included the Franklin Associates (FAL) database to provide impacts for fuels and electricity for the US (PRé Consultants 2007). For materials not covered in the FAL database, the Ecoinvent v1.0 database (Ecoinvent 2004), a comprehensive database for Europe, was used to determine environmental impacts; however, their data were adjusted to US fuels, electricity, and transportation data using FAL processes. Two boundary systems were modeled: 1) the on-site for MDF manufacture only, also referred to as gate-to-gate; and 2) the cradle-to-product gate to encompass all upstream impacts from the MDF product exiting the mill gate to include all material uses back to their in-ground resources. Mass-based allocation was used for all input and output resources and impacts.

System Boundary Conditions

A black-box approach was selected for modeling the LCI of the MDF production process. Whereas a unit process approach was used in earlier CORRIM studies of lumber and plywood production (Milota et al 2005; Wilson and Sakimoto 2005), it is not needed in this case because unlike those processes that have a higher percentage of coproduct that is generated at various steps throughout the manufacturing process, MDF production has little if any coproducts. In a black-box approach for MDF production, all inputs flow into the box and all outputs flow out of the box (Fig 3). For on-site emissions, only those inputs and outputs directly associated with the manufacturing process are considered whether those emissions occur because of on-site combustion of fuels for process heat or operating equipment or those as a result of processing the wood. For the cradle-to-product gate emissions, all impacts are considered including those for the manufacture and delivery of wood residue, fuels, electricity, resin, wax, and scavenger back to their in-ground resources. The system boundary provides the cradle-to-product gate impact from the forest and raw material resources in the ground through all coproduct and product processing steps. Because only a small amount—0.3%—of coproduct was produced during MDF manufacture as wood fuel sold to other manufacturers, the amount is insignificant, and no environmental burden was assigned to it. Also sold was some bark mulch.

Materials Flow

Those materials considered in the LCI analysis included input materials of wood residue, UF resin, wax, and urea scavenger. Other resins were used for making moisture-resistant panels; however, because of their small percentage of use, they were not considered in this study. The other resins included MUF and pMDI. The LCI data of this study is only for UF-resin bonded MDF that represents 98% of panels produced in the survey and the US. Although the nonwood inputs are given on a 100% solids weight, they were brought into the mill as neat at their average percentage of solids; the solids content of each are as follows: UF resin (62%), wax (58%), and urea scavenger (40%) with water as the remainder. The urea scavenger is used to capture excess formaldehyde to reduce its emission from the panel during pressing. The wood residue is representative of

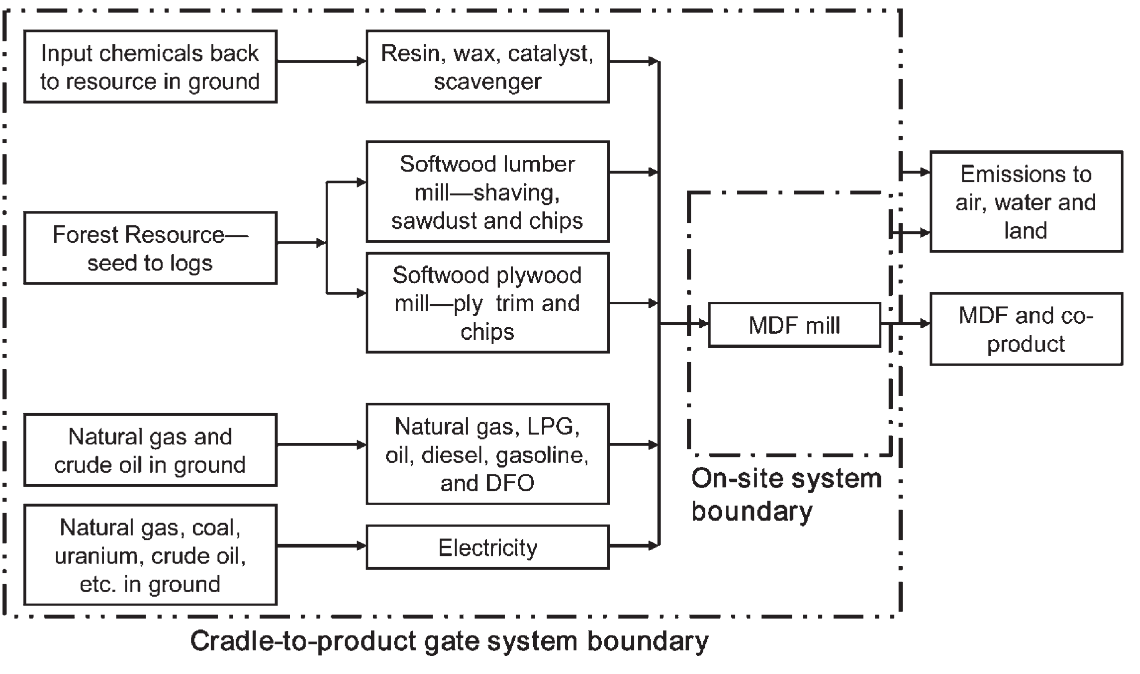

Figure 3. System boundaries for both on-site and cradle-to-product gate impact analyses.

the wood species used to produce lumber and plywood in the major production centers of the US, which primarily includes softwoods for the southeast and Pacific Northwest regions. A small portion of the green chips (37%) and green sawdust (7%) are from hardwoods sources in the northeast. Because LCI data for hardwoods was not in the CORRIM database at the time of the study, softwood LCI data were used as a surrogate for it. The input moisture contents on an oven-dry weight basis for each type of wood residue was as follows: green chips (52%), green sawdust (51%), green shavings (47%), dry shavings (12%), and plywood trim (8%).

Each 1 m^3 of MDF has an oven-dry weight of 741 kg consisting primarily of wood residue (660 kg) and UF resin (75 kg). The wood component represents 89% and the resin 10.1% of the total board weight. Lesser amounts of wax (0.6%) and urea (0.2%) scavenger make up the remainder of the board weight. The board weight and its components are less than the inputs because some material is lost during processing primarily as a result of the sanding operation.

Transportation

The delivery of materials to the mills is by truck, although some resin is delivered by direct pipeline from adjacent resin plants. Table 1 gives the one-way delivery distances for the material inputs. Usually these deliveries have no back haul of other materials.

Assumptions

Specifics on all conditions and assumptions for this LCI study are given in a CORRIM report by Wilson (2008).

Table 1. *One-way delivery distance by truck for input materials to medium-density fiberboard mills.*

Material	Delivery distance (km)
Wood residue	161
Bark hog fuel	84
Urea–formaldehyde resin	134
Wax	134
Urea scavenger	134

Medium-Density Fiberboard Manufacture

Table 2 provides a listing of all inputs and outputs for the on-site manufacture of MDF. These inputs produced 1.0 m^3 of MDF and consisted of 793 kg of industrial wood residue on an oven-dry weight basis that was produced as a coproduct in the manufacture of lumber, plywood, and other primary wood products. These inputs yielded 1.0 m^3 (741 kg) of MDF comprised of wood, resin, wax, and scavenger. A small amount of bark mulch (12.9 kg) and a very small amount of wood fuel (0.06 kg) was produced in the process and sold outside of the system boundary. Also, a small amount of wood

Table 2. *On-site inputs and outputs for the production of 1.0 m^3 of medium-density fiberboard.*

Production data	Unit	Unit/m^3
Inputs		
Wood residue[a]		
Green chips	kg	427
Green shavings	kg	62
Dry shavings	kg	125
Green sawdust	kg	151
Plywood trim	kg	28
Total wood residue	kg	793
Urea–formaldehyde resin[b]	kg	83.3
Wax[b]	kg	5.21
Urea scavenger[b]	kg	1.28
Electricity		
Electricity	MJ	1494
Fuels		
Natural gas	m^3	43
Diesel	L	0.43
Liquid propane gas	L	0.76
Gasoline and kerosene	L	0.13
Distillate fuel oil	L	0.27
Sander dust (wood)	kg	70
In-mill generated wood fuel	kg	54
Bark hog fuel purchased	kg	236
Dirty fuel from in-mill chip wash	kg	2.72
Water use		
Municipal water	L	935
Well water	L	452
Outputs[a,c]		
Medium-density fiberboard (MDF)	kg	741
Bark mulch (sold)	kg	12.9
Wood boiler fuel (sold)	kg	0.06
Wood waste to landfill	kg	2.21
Boiler fly ash to landfill	kg	1.94

[a] All wood and bark weights given as oven dry.
[b] Weight at 100% solids.
[c] Emissions to air, water, and land listed in a separate table.

waste (2.21 kg) and boiler fly ash (1.94 kg) was sent to the landfill. There was also some wood residue fuel generated internally in the manufacturing process—70 kg of sander dust that was burned in the fiber dryers and 54 kg of wood waste that was burned in either the dryer or boiler. Also purchased and not included in the wood residue total was 236 kg of bark hog fuel that was used to provide process heat.

Sources of Energy

Energy for the production of MDF comes from electricity, wood sources, natural gas, and oil, whereas other fuels such as diesel, liquid propane gas, and gasoline are used to operate transport equipment within the mill. With the volatile and increasing fuel and electricity prices, and the interest in reducing fossil fuel use to reduce global warming, these topics will attract considerable attention in the coming years as mills seek to maintain profitability by reducing costs and to address reducing CO_2 fossil emissions. Adding to these concerns is the installation of emissions control systems to meet PCWP MACT regulations (USEPA 2004) that will increase use of natural gas and electricity to operate these systems, resulting in increases of CO_2 fossil emissions. Electricity is used throughout the process to operate equipment within the plant such as conveyors, refiners, fan motors, hydraulic press motors, sanders, and emission control systems. The fuels for equipment are used for loaders and forklifts, and the natural gas and wood fuels are used to provide process heat for flash-tube dryers and presses.

Electricity Use

The source of fuel used to generate the electricity used in the manufacturing process is very important in determining the type and amount of environmental impact as a result of its use. The electricity use on average was 1493 MJ/m^3 (415 kWh/m^3). The breakdown of fuel source to generate the electricity was based on the US average as given by the Energy Information Administration (EIA 2007) for 2004. The dominant fuel source is coal (49.8%) followed by nuclear (19.9%) and natural gas (17.9%). The lesser contributing sources are hydroelectric (6.8%), petroleum (3.0%), and other renewables (2.3%); much smaller quantities are produced by other gases (0.4%) and other (0.2%). The fuel source to generate electricity is important in any LCI because the impacts are traced back to the in-ground source of the fuel used. The efficiency to produce and deliver electricity is relatively low; generation is about 30% energy-efficient, and the average line loss to deliver is about 7%. In PRé Consultant's SimaPro environmental assessment software, no impacts are associated with hydroelectric-generated electricity, whereas combustion of coal and natural gas contribute significant impact values. The generation of electricity by fuel source is used to assign environmental burdens in the SimaPro modeling of the various processes.

Fuel Use as a Heat Source

Wood, whether waste or bark hog, is the primary fuel used in the MDF process. Wood fuel is used for providing process heat for drying the wood residue and heating steam or oil for hot presses. Wood is used for fuel in the form of sander dust that is generated in the process when the panels are sanded to thickness and smoothness; a small amount of additional wood fuel was generated during processing. Three of the four mills used sander dust to fire dryers in addition to the use of natural gas. The sander dust contains about 5% moisture based on its oven-dry weight. One of the mills used wood waste generated within the process to heat dryers in addition to their use of sander dust. Also, two mills purchased bark hog fuel for use in processing. The second largest fuel source is natural gas that is used for dryers, and one of the four mills reported using HAP emissions control devices that use natural gas for their operation. The mill that reported use of a VOC and HAP control system used both RCO and RTO emission control devices for emissions from the dryers and press. Had all four mills used RTOs and/or RCOs, the natural gas and electricity use would have been greater. Even if BFs were installed, the electricity use would have been greater. A small amount of fuel oil was used for process heat and a small amount of fuel was used to operate forklift trucks and handlers within the mill.

Table 3 gives the fuel use on-site energy for manufacturing MDF. The total fuel use for process heat is 9,188 MJ/m^3 (based on the HHV of each fuel) of which 82% is generated through the combustion of wood fuel and the other 18% is from natural gas. In terms of the total energy use of 10,723 MJ/m^3, which includes fuel for process heat and equipment and electricity, the wood fuel energy represents 70%, natural gas energy 15%, and the electrical energy 14%. Wood fuel is a renewable, sustainable resource as opposed to using fossil fuels of oil and natural gas that are neither renewable nor sustainable. The fossil fuel use represents an opportunity for improving sustainability by substituting for it with wood fuel.

On-Site Mill Product and Emissions

On-site outputs for the production of MDF include a small quantity of bark mulch and emissions to air, water, and land (Table 4). Emissions are generated because of the mechanical processing that can result in particulate wood emissions of various sizes, emissions to air that occur when wood and resin are subjected to elevated temperatures during processing, and emissions because of the combustion of fuels such as wood, natural gas, and propane. Emissions to air include particulate and particulate PM10 (less than 10 μm) that occur in refining, drying, sawing, and sanding. Other air emissions include the VOCs that occur in drying, pressing, and panel cooling; recorded emissions of formaldehyde and methanol are used as a measure of the amount of HAPs. HAPs not recorded include acetaldehyde, acrolein, and phenol. All mills in the survey reported VOC, formaldehyde, and methanol, whereas no mills reported acrolein,

Table 3. *On-site fuel, electricity, and energy[a] use in the manufacture of 1.0 m^3 of medium-density fiberboard.*

Energy use	Unit	Unit/m^3	MJ/m^3	Percent
Fuel for process heat				
Fossil fuel				
Natural gas	m^3	43	1657	
Distillate fuel oil (DFO)	L	0.027	11	
Renewable fuel				
Sander dust	kg	70	1465	
In-mill generated wood fuel	kg	54	1124	
Bark hog fuel purchased	kg	236	4932	
Subtotal			9188	85.7
Fuel for equipment				
Diesel	L	0.43	17	
Liquid propane gas	L	0.75	20	
Gasoline and kerosene	L	0.13	5	
Subtotal			41	0.4
Electricity				
Electricity purchased	MJ	1493	1493	13.9
Total energy			10,723	100

[a] Higher heating values (HHV) used; coal 26.2 MJ/kg, DFO 45.5 MJ/kg, liquid propane gas 54.0 MJ/kg, natural gas 54.4 MJ/kg, diesel 43.4 MJ/kg, gasoline 54.4 MJ/kg, wood/bark 20.9 MJ/kg, and electricity 3.6 MJ/kWh.

Table 4. *On-site reported outputs for the production of 1.0 m^3 of medium-density fiberboard.*

Production output	kg/m^3
MDF	741
Coproduct	
Bark mulch (sold)	12.9
Emissions to air[a]	
Carbon dioxide, biogenic[b]	762
Carbon dioxide, fossil (GHG)[b,c]	83.4
Carbon monoxide[b]	5.04
Methane (GHG)[b]	0.0024
Nitrogen oxides	0.38
Sulfur oxides	0.0073
Total VOC	0.84
Particulate	0.36
Particulate (PM10)	0.29
Acetaldehyde (HAP)[c]	NR[d]
Acrolein (HAP)	NR
Formaldehyde (HAP)	0.16
Methanol (HAP)	0.22
Phenol (HAP)	NR
HAPs	NR
Emissions to water[a]	
Suspended solids	0.010
BOD	0.0072
Ammonia nitrogen	0.0023
Emissions to land[a]	
Boiler fly ash	1.94
Wood waste landfill	2.21

[a] Emissions data reported from surveys.
[b] Emissions determined by output from fuel entries into SimaPro for site emissions.
[c] HAP, hazardous air pollutant; GHG, greenhouse gas.
[d] NR, not reported.
VOC, volatile organic compound; BOD, biological oxygen demand.

phenol, or propionaldehyde, and only one mill reported acetaldehyde. Only mills reporting a given emission were included in the weight-averaging for that emission, except the one value for acetaldehyde was not used. The CO_2 for biogenic (wood) and fossil-fuel sources, carbon monoxide, and methane that were not reported in the survey were determined by entering the actual fuel use for both heat sources and equipment into the SimaPro software. These emission values were determined using the Franklin Associates database for US fuels (FAL 2004). The CO_2 for biogenic (wood) and fossil fuel sources was tracked separately. The CO_2 from combustion of biogenic sources is not considered a greenhouse gas (GHG) that contributes to global warming according to the US Environmental Protection Agency because its carbon life cycle is closed loop in that the CO_2 is reabsorbed by the growing of trees, releasing oxygen to the atmosphere and using the carbon to make more wood (USEPA 2003).

Cradle-to-Product Gate Resource Use and Emissions

The LCI for the production of MDF covers its cycle from tree seed as well as the components of other additives and in-ground resources through the manufacture of MDF. The LCI includes all manufacturing inputs listed in Table 2 back to resources shown for the system boundary of Fig 3. The cradle-to-gate does not include some items that contribute to less than 1% of the environmental impact such as packaging materials and shipping dunnage. Table 5 gives the raw materials, energy, and emissions for the cradle-to-gate inventory to produce 1.0 m^3 of MDF. The in-ground raw materials include coal, natural gas, limestone, crude oil, uranium, and water use. Because life-cycle studies involve tracing resource use back to its in-ground source, some materials or substances can involve many steps of backtracking that can result in a large number of substances of insignificant quantities. For this study, a filter was used to remove insignificant substances from the listing. Quantities of raw materials of 1.0E-02 kg/m^3 and less were not

Table 5. *Life-cycle inventory output of allocated materials and emissions cradle-to-product gate for the production of 1.0 m^3 of medium-density fiberboard.*

Life-cycle inventory	Unit
Raw materials	kg/m^3
Carbon dioxide in air[a]	2.09E+03
Calcite in ground	1.38E-01
Clay in ground	3.94E-02
Coal in ground	1.19E+02
Crude oil in ground	4.44E+01
Gravel in ground	1.16E+00
Iron ore in ground	1.28E-02
Limestone in ground	2.06E+01
Natural gas in ground	1.23E+02
Nickel in ground	3.58E-02
Sodium chloride in ground	6.44E-02
Tree seeds	6.79E-04
Uranium in ground	5.20E-04
Water unspecified natural origin	1.59E+03
Water well in ground	6.15E+02
Wood fuel	3.92E+02
Energy	MJ/m^3
Energy from hydropower	2.10E+02
Electricity from other gases	6.43E+00
Electricity from other renewables	3.70E+01
Emissions to air	kg/m^3
Acetaldehyde (HAP)[b]	5.92E-04
Acetic acid	6.60E-04
Acetone	2.49E-04
Acrolein (HAP)	4.41E-06
Aldehydes, unspecified	1.20E-02
Alpha-pinene	2.32E-03
Aluminum	6.24E-04
Ammonia	2.25E-01
Barium	1.72E-03
Benzene	2.15E-03
Beta-pinene	9.00E-04
Butane	1.30E-03
Carbon dioxide, biogenic	8.20E+02
Carbon dioxide, fossil (GHG)[b]	5.86E+02
Carbon disulfide	2.61E-04
Carbon monoxide	6.55E+00
Chlorine	3.06E-03
Dinitrogen monoxide (GHG)	3.70E-03
Formaldehyde	1.67E-01
HAPS	3.80E-01
Hydrocarbons, unspecified	4.97E-03
Hydrogen chloride	2.24E-02
Iron	1.83E-03
Manganese	3.55E-03
Mercury	9.10E-06
Metals, unspecified	7.59E-05
Methane (GHG)	1.36E+00
Methanol (HAP)	2.46E-01
Nitrogen oxides	3.26E+00
Nitrous oxide (GHG)	2.56E-03

(continued)

Table 5. *Continued.*

Life-cycle inventory	Unit
NMVOC (nonmethane)	1.48E+00
Organic substances, unspecified	2.33E-01
Particulates	3.85E-01
Particulates (unspecified)	1.50E-02
Particulates, <10 μm	8.16E-01
Particulates <2.5 μm	7.54E-02
Particulates, >10 μm	5.88E-02
Particulates >2.5 μm, <10 μm	3.00E-01
Particulates, unspecified	3.13E-01
Pentane	2.22E-03
Phenol (HAP)	1.93E-03
Potassium	3.05E-01
Sodium	7.51E-03
Sulfur dioxide	5.09E-02
Sulfur oxides	6.17E+00
Toluene	3.88E-04
Vanadium	1.66E-03
VOC	9.32E-01
Zinc	1.75E-03
	Bq/m^3
Noble gases, radioactive, unspecified	3.59E+04
Radioactive species, unspecified	5.77E+06
Radon-222	6.95E+04
Emissions to water	kg/m^3
Aluminum	8.58E-04
Ammonia	3.36E-04
Ammonium, iron	2.34E-02
BOD5	1.60E-02
Boron	1.15E-02
Cadmium, ion	2.97E-04
Calcium, ion	5.99E-03
Chloride	3.09E-01
Chromium	3.02E-04
COD	1.06E-01
DOC	1.22E-02
Fluoride	1.30E-02
Formaldehyde	4.17E-03
Iron	1.63E-02
Iron, ion	9.62E-04
Lead	1.58E-05
Magnesium	2.17E-04
Manganese	9.36E-03
Mercury	9.10E-06
Metallic ions, unspecified	9.83E-04
Methanol	1.25E-03
Nickel, ion	1.98E-04
Nitrate	1.17E-04
Nitrogen	7.88E-03
Nitrogen, organic-bound	1.28E-04
Oils, unspecified	1.16E-01
Organic substances, unspecified	2.08E-02
Phenol	4.21E-04
Phosphate	1.09E-02
Phosphorus	4.17E-04

(continued)

Table 5. *Continued.*

Life-cycle inventory	Unit
Potassium, ion	1.13E-04
Silicon	4.69E-02
Sodium, ion	4.29E-03
Solids, inorganic	2.20E-04
Solved solids	6.53E+00
Sulfate	3.01E-01
Sulfuric acid	2.87E-03
Suspended solids	1.01E-02
Suspended solids, unspecified	2.75E-01
TOC (total organic carbon)	1.22E-02
Zinc, ion	1.33E-04
Waste	kg/m^3
Packaging waste	2.83E-01
Waste, inorganic	4.76E-01
Waste, solid	6.79E+01
Wood waste	1.66E-01
Emissions to land	kg/m^3
Boiler fly ash	1.94E+00
Wood waste	2.21E+00

[a] Includes CO_2 uptake for carbon store in wood component of medium-density fiberboard (1268 kg CO_2 equivalent) and in wood fuel (820 kg CO_2 equivalent).

[b] HAP, hazardous air pollutant; GHG, greenhouse gas.

VOC, volatile organic compound; BOD5, five-day biological demand; COD, chemical oxygen demand; DOC, dissolved oxygen carbon.

included in the listing. The filter varied depending on whether it was for raw material or emission to air, water, or land. The exception was for substances that are highly toxic such as mercury and uranium (as a result of the generation of electricity) where values less than the cutoff criteria value were recorded.

For recordkeeping only, wood used for fuel is listed, although not a true raw material in the sense that its origin is a tree seed and is both renewable and sustainable. Some sources of energy or fuels cannot be traced back to their in-ground resource. Such energies include energy from hydroelectric power, electricity from other gases of unknown sources, and electricity from renewables that are not defined in terms of identifiable fuels. These are listed in a separate category defined as "energy."

Emissions for the cradle-to-product gate scenario are also listed in Table 5. The emissions to air and water used a cutoff value of 1.0E-04 kg/m^3, to land used a cutoff of 1.0E-02 kg/m^3, waste of 2.0E-01 kg/m^3, and radiation terms used a cutoff of 1.0E+04 Bq/m^3. The GHG and HAP emissions associated with the production of wood products are identified. Raw materials and emissions for a cradle-to-gate inventory are greater than those resources and emissions that occur at the production site; this is true for all processes. The percentage contribution of on-site to cradle-to-gate emissions to air is shown in Fig 4. On-site emissions for manufacturing MDF are small for those emissions such as CO_2 fossil, NO_x, and particulates, whereas those emissions because of either combustion of wood fuel and processing MDF are larger for CO_2 biogenic, VOC, formaldehyde, and methanol. On-site CO_2 fossil emission is only 14% of the cradle-to-gate emission.

Of significance is the raw material use of "carbon dioxide in air" that accounts for the uptake of CO_2 during the growing of trees that stores carbon in wood residue and wood fuel. The CO_2 uptake is accounted for at harvest in modeling and its mass allocated to all wood products, coproducts, and fuel going downstream through the various stages of processing. This uptake is treated as a carbon store in wood for its life cycle until it either decomposes or burns. To produce 1.0 m^3 of MDF, the resource of "carbon dioxide in air" is 2088 kg that can be used to offset CO_2 emissions from wood, fossil fuel use, and some CO_2 in the atmosphere. The breakdown of the CO_2 uptake by contributor is 1268 kg for the CO_2 equivalent (CO_2 equiv) of carbon store in the wood component of MDF and 820 kg for the wood fuel used in the production of wood residue and MDF. It is common practice for European LCI modelers to account for the carbon store of wood in this manner. An expanded discussion on carbon store and footprint is given later in the "Carbon Flux" section.

Embodied Energy

The embodied energy to produce MDF can be given in several ways. For this study, it is useful to examine the energy contribution in terms of both its in-ground fuel source and by the various input substances or process components.

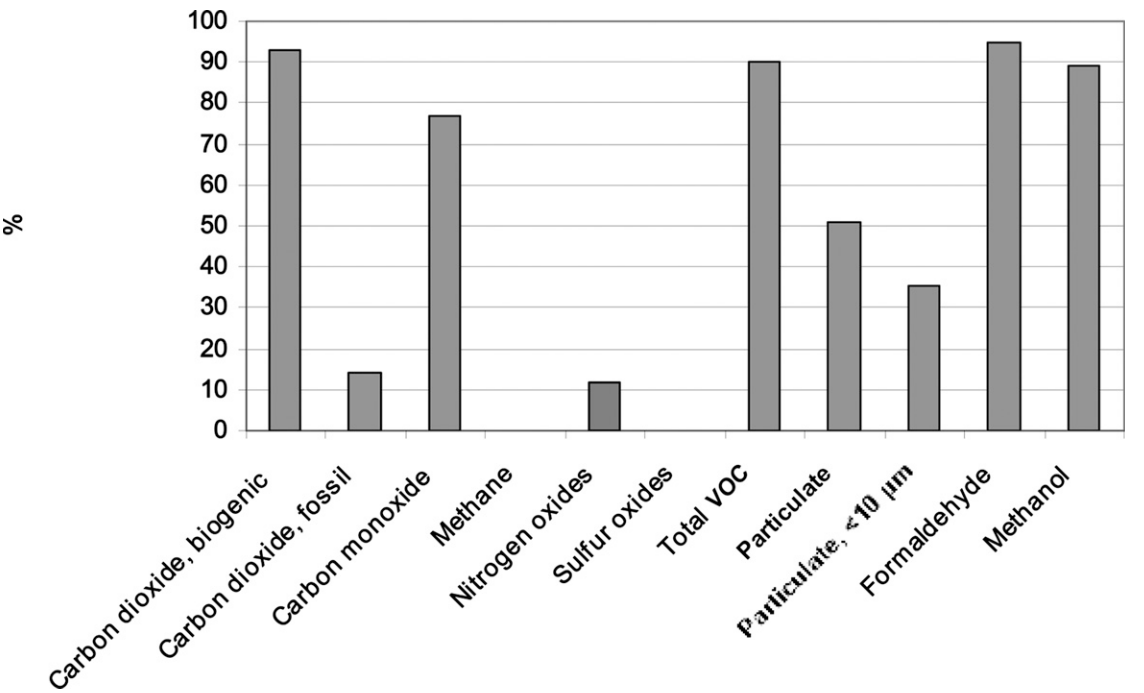

Figure 4. Contribution percentage of on-site to cradle-to-product gate emissions for medium-density fiberboard.

Table 6 gives the cumulative energy use from cradle-to-product gate for the production of MDF in terms of its in-ground fuel source. To produce 1.0 m^3 of MDF, it takes a total of 20,707 MJ based on the HHV of the fuels. Wood fuel use provides 39.6% of the energy followed by natural gas (32.3%), coal (15.1%), and oil (10.8%) with all other sources of minor significance. The embodied energy is higher than if more natural gas was used to substitute for wood fuel because the combustion of wood fuel is less efficient resulting in more wood fuel to obtain the same energy need. The importance of the wood fuel contribution is that it is renewable, whereas the other fuel sources of natural gas, oil, and coal are not. The nonrenewable portion can be considered as an opportunity for reducing the use of fossil fuels by substituting with wood renewable fuels, at least for some practical portion of fuel use.

Energy contribution by the input component can be valuable in assessing the major contributors and for identifying opportunities for reducing energy use. Table 7 gives the embodied energy breakdown for manufacturing MDF from tree seed to product at the exit gate of the mill. The total energy is 20,707 MJ/m^3 with the in-mill wood fuel, electricity, and UF resin being the major contributors at 37.3%, 21.8%, and 18.9%, respectively, followed by in-mill natural gas and wood residue use at 10.7% and 8.1%, respectively, with all other contributors of much less significance. Transportation of wood residue, resin, wax, and scavenger to the mill represents only 1.6% of the total energy. About 29% of the energy contribution is to produce the wood residue, UF resin, wax, and scavenger. Energy to provide manufacturing process heat and electricity represents 69% of the total.

Sensitivity Analysis

A sensitivity analysis was conducted per ISO protocol that involved examining the impact of varying an input parameter such as fuel to a process and examining the magnitude of the change of an output parameter such as resource use or CO_2 (fossil) emission. The sensitivity analysis first assessed the input parameters such as wood residue, resin, catalyst, wax, scavenger, fuels, and electricity, transportation, and their impact on emissions to air, land, and water. A test was done to determine whether changing a specific input such as wood fuel would result in an expected change for output emissions. The magnitude of the impact was found to be dependent on the input parameter and also on the output parameter of interest. For a complete sensitivity analysis, see Wilson (2008).

Carbon Flux, Store, and Footprint

Climate change has become a major issue as government agencies, companies, and indivi-

Table 6. *A breakdown by fuel source[a] to produce 1.0 m^3 of medium-density fiberboard cradle-to-product gate.*

Substance	MJ/m^3	Contribution (%)
Coal in ground	3123	15.1
Natural gas in ground	6686	32.3
Crude oil in ground	2243	10.8
Uranium in ground	198	1.0
Wood and bark fuel[b]	8204	39.6
Electricity from other gases	6	0.03
Electricity from other renewables	37	0.2
Energy, hydroelectric power	210	1.0
Total	20,707	100

[a] Energy values based on their higher heating values (HHV) of Table 4, uranium at 381,000 MJ/kg.
[b] Includes all sander dust, self-generated hog, purchased, and direct-fired wood fuels.

Table 7. *A breakdown by energy contributor to produce 1.0 m^3 of medium-density fiberboard cradle-to-product gate.*

Process component	MJ/m^3	Contribution (%)
Wood residue	1683	8.1
Urea–formaldehyde resin	3924	18.9
Wax	266	1.3
Urea scavenger	33	0.2
Transportation diesel	321	1.6
Natural gas	2206	10.7
Wood fuel	7718	37.3
Distillate fuel oil	12	0.1
Electricity	4519	21.8
Diesel and other equipment fuels	25	0.1
Total	20,707	100

duals look for ways to reduce GHG emissions that contribute significantly to it. The major GHG is CO_2 with lesser contributions from methane (CH_4) and nitrous oxide (N_2O), although there are others such as fluorinated gases that do not occur in this study. Two possible approaches to reducing GHG emissions include storing carbon so that it is not in the atmosphere in the form of CO_2 and reducing the use of fossil fuels that when combusted release CO_2 to the atmosphere. Carbon flux through a product's life cycle can be used to assess the total impact of CO_2 on global warming and climate change as measured by a sum of its carbon store and carbon footprint.

Carbon is stored in wood whether in trees, products, or fuel. When trees grow, they remove CO_2 from the atmosphere to form wood substance that is comprised of about one-half by weight of carbon, releasing oxygen back into the atmosphere. The carbon remains stored in the wood until it is burned or breaks down because of chemical action or decay. This characteristic of wood to store carbon can be used in a management plan to reduce climate change.

Carbon in wood was tracked for the production of MDF in and out of the manufacturing process to determine the balance for its carbon flow. This analysis followed carbon from the inputs of wood materials through production of product, coproduct, waste, and the generation of emissions. The percentage of carbon in wood was taken as an average value for those referenced in earlier CORRIM LCI studies of softwood lumber, plywood, and oriented strandboard as 52.4% (Milota et al 2005; Wilson and Sakimoto 2005; Kline 2005) that provided the input wood residue LCI data. The input consists of wood chips, shavings, sawdust, plywood trim, and bark hog fuel and the output consists of MDF and small quantities of bark mulch, wood fuel, waste, and wood-related emissions such as CO_2 biogenic because of combustion of wood fuel (Wilson 2008). The difference between the inputs and outputs is slightly less than 5% with more wood carbon flow out than in, which can be mostly attributed to the greater than expected CO_2 biogenic emissions given by the FAL database for wood fuel combustion.

The CO_2 equiv of carbon store in 1.0 m^3 of MDF is –1268 kg based on 52.4% carbon component of the wood (Wilson 2008). The carbon store is treated as a negative value when determining the carbon flux. CO_2 equiv is determined by the molar mass ratio of CO_2 to carbon of 44/12 for 3.67 times the 346 kg carbon content of the wood component in MDF. Whereas there is also carbon store in other MDF components of UF resin (25% by weight), wax (85%), and urea scavenger (20%), these carbon stores are not counted in the carbon flux accounting because they are derived from fossil feedstock of crude oil and natural gas (Wilson 2009, 2010). Only carbon store in wood is considered in the flux because its carbon cycle is continuously renewing by the growing of trees. The carbon cycle of fossil feedstock is not continuously renewing, at least within our time cycle. Wood carbon stores renew within decades, whereas stores in fossil fuels renew in millions of years. The carbon store remains in the MDF for the life of its service, which can be 10 – 80 yr. The carbon store can be even longer if placed in a modern landfill where much of it can last an additional 100 yr and more (Skog 2008). When the CO_2 is finally released into the atmosphere, it is reabsorbed by the growing of trees to form more wood, thus continuously renewing its carbon cycle.

The carbon footprint of a product, process, or service is based on the total CO_2 equiv of GHG emitted. CO_2 emission as a result of the combustion of wood fuel is not included in the footprint because it is offset by its own carbon store. Considering the combustion of wood fuel as carbon-neutral in this manner is consistent with many groups overseeing environmental concerns (USEPA 2003; IPCC 2007; BSI 2008) that state that biomass fuel is considered global warming impact-neutral. The carbon footprint includes emissions of CO_2, CH_4, and N_2O in terms of their CO_2 equiv based on their atmospheric 100-yr radiative forcing factors (IPCC 2007). The carbon footprint of MDF in terms of its kg CO_2 equiv is equal to the kg CO_2 fossil emissions plus 25 times the kg CH_4 emissions plus 298 times the kg N_2O emissions. Figure 5 gives the carbon footprint, carbon store, and net carbon flux for MDF. The cradle-to-product gate carbon footprint is 621 kg CO_2 equiv, whereas the on-site footprint for the manufacture of MDF is only 83.4 kg CO_2 equiv. The on-site footprint is only 23% of the total cradle-to-product gate emissions. The carbon store of –1268 kg CO_2 equiv in MDF can be used to offset the cradle-to-product gate carbon footprint of 621 kg CO_2 equiv, leaving an offset of –647 kg CO_2 equiv that can be used against additional CO_2 in the atmosphere and in turn reduce the impact on climate change further (Fig 5). This remaining offset can be used against additional CO_2 emissions beyond the product gate because of product use, disposal, or recycle and possibly against CO_2 in the atmosphere. Because of the large carbon store for MDF that more than offsets its carbon footprint through manufacturing and beyond, it can be considered a better than climate-neutral material. A climate-neutral material would have a carbon store equal to its footprint.

DISCUSSION

The data documented in this report on the manufacture of MDF form a foundation for the scientific assessment of its environmental performance. The data can be used in a number of ways to show the favorable performance of MDF in environmental issues such as sustainability, global warming, climate change, carbon storage, biomass fuel use, green purchasing, and green building. The data can be used as stated or in a LCA to determine impacts of process changes and to compare with various alternative materials or assemblies of materials. For comparison of the results of this study with other

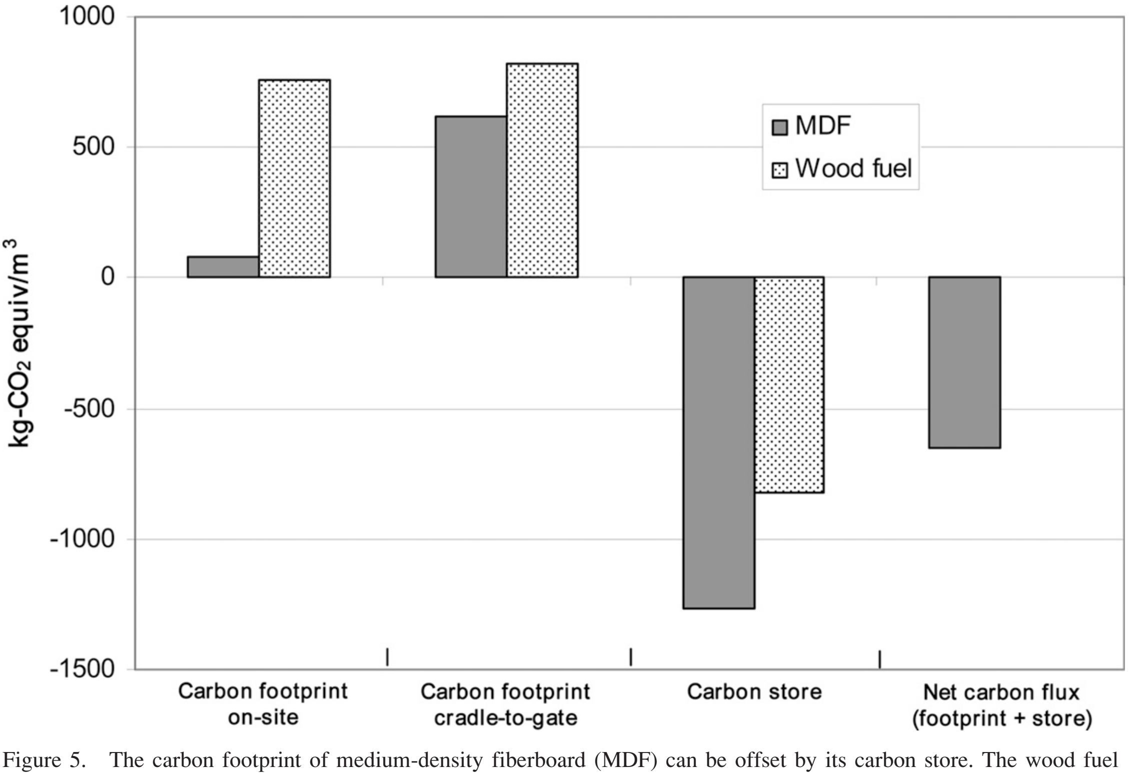

Figure 5. The carbon footprint of medium-density fiberboard (MDF) can be offset by its carbon store. The wood fuel values are not considered in the MDF footprint values because wood fuel is considered carbon-neutral in that its combustion emission is offset by its store.

processes or materials, it is important that they be compared using the same system boundary conditions and when comparing energy use using the higher heating values of the fuels.

The quality of the LCI data collected in survey of the MDF manufacturing process was judged to be high based on analysis of the data and on mass and energy balances. To further assess data quality, a comparison was made with LCI data in the literature. A comparison was made with LCI data reported on MDF production in Spain (two mills) and Chile (one mill) (Rivela et al 2007). For a complete comparison of these LCI studies in terms of input and output data for manufacturing MDF, see Wilson (2008). The most obvious part of this comparison is that this CORRIM study gives broader system boundary conditions covering from resources in the ground to product and gives far more specifics such as moisture and solids contents of inputs. The Rivela et al (2007) study ignores the environmental impact contribution of generating and harvesting the forest as well as the production of chips, shavings, and sawdust for input to the mills. Therefore, the only comparison made was for the MDF manufacturing on-site inputs and outputs. Based on this comparison, some values are similar such as electricity and material use, whereas fuel use for the Rivela et al (2007) study relies totally on wood fuel but seems inconsistent in that they report twice the emissions of NO_x that could be contributed by natural gas combustion, although none was reported. The Rivela et al (2007) study also has much less reported fuel use than this study. Of significance is that the CO_2 emissions for this CORRIM study is tracked separately in terms of its fuel source such as biogenic for wood and fossil for natural gas combustion. Despite these differences, the production input values are relatively similar.

The International Panel for Climate Change (IPCC) described three strategies associated with wood to reduce CO_2 in the atmosphere. Two of the three strategies included the use of wood products (IPCC 1996). They later state that the substitution affect of wood products for fossil-fuel-intensive products provides cumulative and permanent avoidance of fossil carbon emissions, whereas storage in trees provides limited and possibly transient emissions avoidance. Simply put, it is environmentally more effective to use trees for products that displace fossil-fuel-intensive products for reducing carbon emissions to the atmosphere than it is to store the carbon in trees (IPCC 2001a, 2001b). These same strategies can be addressed with the manufacture and use of MDF where wood is used as fuel to displace fossil fuels for a significant portion of its energy need and as a product to displace fossil-fuel-intensive products.

CONCLUSIONS AND RECOMMENDATIONS

An LCI was developed for the production of 1.0 m^3 of MDF produced in the US. The system boundary went from resources in the ground through the manufacture of MDF. The quality of the primary data collected by survey questionnaire of MDF manufacturers was high as judged by assessments for outliers, a mass balance of material in and out of the process, and an energy balance for drying wood within the process. Primary data were also used for resin and wood residue use from other CORRIM studies. Secondary data were used for other inputs of electricity, fuels, and some chemicals. The data set and reporting are in compliance with both CORRIM and ISO protocol and guidelines for LCI studies. As a result of the LCI analyses of both on-site and cradle-to-product gate system boundaries, the following conclusions are made:

- On-site emissions for manufacturing MDF represent a significant contribution to the total cradle-to-product gate emissions for those related to the use of wood fuel—CO_2 biogenic and CO—and those related to the drying and hot pressing—VOC, particulates, formaldehyde, and methanol. Whereas on-site contribution to emissions are small for those related to the combustion of fossil fuels—CO_2 fossil, nitrogen oxides, and sulfur oxides, unlike fossil fuel emission, the wood fuel emission does not contribute to global warming or climate change.

- The embodied energy to produce 1.0 m^3 of MDF consists of fuels and electricity used on-site and the fuels used cradle-to-product gate that includes the on-site as well as those fuels to generate and deliver wood, chemicals, fuels, and electricity to the mill. The on-site energy use was 10,723 MJ and the cradle-to-product gate energy use was 20,707 MJ, all based on the HHVs of the fuels. Of the on-site process energy use, wood fuel provides 82%, and if the energy for electricity use is considered in the total, the wood fuel provides 70%. The use of wood fuel is important because it is a sustainable, renewable fuel that is substituting for fossil fuel a nonrenewable fuel, and wood fuel is considered global-warming and climate-change neutral.
- The favorable effect of carbon storage by both wood and bark carries over into the manufacture of MDF, which can be used to offset CO_2 emissions not only from cradle-to-gate but for product use and disposal as well as some CO_2 in the atmosphere. To produce 1.0 m^3 of MDF, the CO_2 removed from the air because of its carbon store is –1268 kg CO_2 equiv that can be used to offset the CO_2 equiv of the LCI output GHG emissions of 621 kg CO_2 equiv—its carbon footprint—because of the combustion of fossil fuel from in-ground resources to product. This leaves a net carbon flux of –647 kg CO_2 equiv as a credit to offset CO_2 because of its beyond-mill product use and in the atmosphere. This further reduces the impact of GHG emissions on global warming and climate change. This carbon store remains in the MDF for the life of its service and even longer if recycled or placed in a modern landfill where much of it can last for over 100 yr. This outcome is consistent with the IPCC that it is environmentally more effective to use trees as fuel and products that displace fossil fuel and fossil-fuel-intensive products than it is to store the carbon in trees.

This study provides a comprehensive database for the LCI of MDF. The data should be used as the basis for any LCA of its environmental performance to improve processing or to compare with other materials. When comparing the data in this study with other processes and products, it is important to use the same system boundary conditions and fuel energy values. These LCI data will be available to the public in a CORRIM comprehensive report at www.corrim.org (Wilson 2008).

To fully benefit from the availability of the LCI database for MDF, the following additional studies are recommended: 1) extend LCI data beyond the production gate through its use, disposal, and recycle life; 2) conduct LCA studies of MDF for various uses; 3) extend the study on the impact of increasing the substitution of wood for fossil fuels; and 4) conduct a carbon flow analysis of MDF beyond the product gate to include use, disposal, and recycle.

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