CORRIM: Phase II Final Report

Module G

Medium Density Fiberboard (MDF): A Life-Cycle Inventory of Manufacturing Panels from Resource through Product

June 2008

Prepared by:

James B. Wilson[1]

[1] Wilson is the Principal Investigator and Professor Emeritus, Department of Wood Science and Engineering, Oregon State University, Corvallis, OR 97331-5751.
jim.wilson@oregonstate.edu,541-737-4227

Acknowledgements

This research project would not have been possible without the financial and technical support provided by the USDA Forest Service Forest Products Laboratory (04-CA-11111137-094), CORRIM's contributing University members, and the contributions of many companies. Special recognition is extended to the Composite Panel Association and its membership who provided technical assistance in the form of survey production data and technical review, as well as financial support. Any opinions findings, conclusions or recommendations expressed in this article are those of the authors and do not necessarily reflect the views of contributing entities.

Executive Summary

The objective of this study was to develop a life-cycle inventory (LCI) for the production of medium density fiberboard (MDF) as manufactured in the U.S. The data are needed to scientifically document the favorable environment performance of MDF for such uses as governed by the many new green building standards, purchasing guidelines, energy and global warming related policies.

MDF is considered a non-structural panel and is used for production of furniture, cabinets, tables, countertops, and millwork. Input materials to produce MDF include the wood residue comprised of shavings, sawdust and chips (all co-products from the production of other wood manufacturing processes), urea-formaldehyde resin, wax and scavenger, as well as all fuels and electricity use. The LCI study was conducted based on ISO 14040 and 14044 standards and CORRIM protocol which specify methodology, analyses and reporting components and format. A survey was conducted of the MDF manufacturers to collect all pertinent production data needed for the LCI study. To complete the LCI from cradle-to-product gate, previously reported data by CORRIM were included for the production of wood residue, forest resources, resin, and transportation.

The life-cycle inventory involves the collection and quantification of all inputs and outputs for a product through its life cycle. This study covers the cycle from the forest resource through the production of MDF, referred to as a cradle-to-product gate analysis. The analysis involves inputs such as resources, fuels, electricity, and chemicals, and outputs such as product, co-product, and emissions to air, water, and land.

Four MDF manufacturing mills were surveyed. The responses represented 2004 production data for 27% of total U.S. production. The functional unit of MDF for the analysis is 1.0 m^3, although the U.S. industry value of 1.0 thousand square feet (MSF) of ¾-inch thickness basis is also given. The average production of the surveyed mills was 208,305 m^3 of MDF at an average dry density of 741 kg/m^3. The MDF panel is comprised of 89.1 % wood, 10.1% urea-formaldehyde resin, 0.6% wax, and 0.2% urea scavenger—all on an oven dry or 100% solids basis weight.
The quality of the LCI data collected for the manufacture of MDF was high as judged by assessments for outliers, mass balances of material in and out of the process, and energy balances for drying the wood residue.

Assigning of environmental burden in the production of MDF was totally to the product since no other co-products of significant mass were sold outside the boundary system. Burdens for the input wood residue and resin came with their assigned burdens based on their actual production and a mass-based allocation from other CORRIM wood product studies.

The embodied energy to produce MDF consists of fuels and electricity used on-site and those used off-site to generate and deliver fuels and electricity to the mill, and those to manufacture input materials such as wood residue, resin, wax and scavenger. The on-site energy which includes all fuels and electricity was 10,723 MJ/m^3. Of the fuels used on-site to provide process heat, wood fuel provided 82% of the energy, and in terms of the total energy use which includes electricity use, wood fuel provided 70%. This is important since wood is a sustainable, renewable fuel that is substituting for fossil fuel, a non-renewable resource; in addition, CO_2 emissions from the combustion of wood fuel are said not to contribute to global warming. The other 18% of the process heat was provided by natural gas. The electricity use on-site was 1,494 MJ/m^3.

The embodied energy of manufacturing MDF from the in-ground resources through product manufacture was 20,707 MJ/m^3. A breakdown of the energy in terms of its contributors can be stated in terms of its fuel type use or major input component. In terms of fuel type the major contributors are wood at 39.6%,

natural gas at 32.3%, coal at 15.1%, oil at 10.8%, plus a number of lesser fuel contributors. In terms of its major input component contributors, wood fuel is 37.3%, electricity 21.8%, urea-formaldehyde resin 18.9%, wood residue at 8.1%, and a large number of other minor contributors that totaled 13.9%. Wood for fuel as an energy source plays a significant and favorable environmental role, its increased use should be explored further.

Of the on-site air emissions for manufacturing MDF, wood fuel generates 762 kg/m^3 of CO_2, some of the CO that totaled 5 kg, and almost all of the VOC (0.84 kg), particulate (0.65 kg), formaldehyde (0.16 kg) and methanol (0.22 kg). Combustion of natural gas and use of a small amount of fuels to operate fork lifts generated 83.4 kg/m^3 of CO_2, some of the CO and methane, and most of the NO_x and SO_x, with a small amount contributed by combustion of wood fuels. Emissions of CO_2 biogenic as a result of the combustion of wood has a neutral impact on global warming according to the EPA, whereas CO_2 fossil emission such as from the combustion of natural gas, contribute significantly to global warming. Only a small amount of solid waste is generated on-site, with 1.94 kg of boiler fly ash and 2.21 kg of wood waste going to the landfill. Of the total emissions from cradle-to-product gate, the on-site emissions contribute 93% of CO_2 biogenic, 14% of CO_2 fossil, 77% of CO, 26% of formaldehyde, 27% of methanol, 12% of NO_x, 38% of total particulates, and 90% of VOC.

Carbon storage occurs in trees as a result of CO_2 uptake as they grow, using carbon to form wood substance and releasing oxygen back to the atmosphere. Carbon stored in trees—in both wood and bark—is important to prevent its emissions as CO_2 to the atmosphere which would contribute to greenhouse gases and their impact on global warming. The carbon remains stored in wood products such as MDF or as its waste in the landfill until it either combusts or decays. About half the mass of wood and bark is carbon; to determine the equivalent of CO_2 that was removed from the air to form the wood and bark whether for product or fuel, multiply their carbon content in kg by 3.67 kg CO_2/kg which is the molar mass ratio of CO_2 to C of 44 to 12. In the life cycle of MDF from the tree seed to product, to produce 1.0 m^3 of it the amount of carbon dioxide removed from the atmosphere is 2,088 kg which can be used to offset 820 kg of CO_2 biogenic and 586 kg of CO_2 fossil emissions. This leaves a credit of 682 kg to offset other greenhouse gas emissions from processing, delivery, product use and disposal, with remaining credit to offset some CO_2 in the atmosphere; in turn reducing their impact upon global warming. The carbon store remains in the MDF for the life of its useful service and even longer if recycled or placed into a modern landfill where it can last for over a 100 years; when the MDF breaks down it releases the CO_2 back to the atmosphere.

A sensitivity analysis was conducted to examine the impact the fuel type use has on the MDF manufacturing process. To conduct the analysis the contribution of process heat by wood fuel was decreased from 82% to 0% and the natural gas use increased from 18% to 100%. For the LCI from cradle-to-product gate, the natural gas in the ground resource increased by 143% and water use decreased substantially. Emissions increased for CO_2 fossil (68%), methane (86%)—both contributors to global warming—and NO_x (19%) and SO_x (100%). With concern over global warming, substituting natural gas for wood fuel to generate process heat for manufacturing would be a poor decision for the environment and resource depletion.

This study provides a comprehensive database for the life-cycle inventory of MDF. The data should be used as the basis for any life-cycle assessment of its environmental performance to improve processing or to compare to other materials. This data will be available to the public at www.corrim.org and through the U.S. LCI Database at www.nrel.gov/lci/.

To obtain full benefit from the availability of the LCI database for MDF the following additional studies are recommended: 1) extract pertinent data to document its favorable environmental performance, 2) develop life-cycle inventory data from the MDF mill's output gate through its incorporation into products such as office and residential furniture through their service life and eventual disposal or recycle, 3) conduct a life-cycle assessment of MDF in comparison to alternative materials and products, and 4) extend the study of the fuel type and amount of its use on its impact on the environment, human health, and resource depletion to foster increased substitution of wood for fossil fuel.

Table of Contents Page

List of Figures **Page**

List of Tables **Page**

1.0 Medium Density Fiberboard (MDF)

1.1 Introduction

The objective of this study is to develop the life-cycle inventory (LCI) data for the composite wood panel product medium density fiberboard which is commonly referred to as MDF. An LCI consists of an accounting of all inputs and outputs of a material from its resources in the ground through production of a product—this is referred to as a cradle-to-product gate study. LCI data are invaluable when it comes to establishing the *greenness* of a product and for comparison to competitive materials. The data forms the foundation for the scientific assessment in terms of a variety of environmental performance measures. It provides data that can be used to establish the performance of MDF for many green type standards, guidelines and policies. Issues where the data can be used are sustainability, global warming, climate change, carbon storage, carbon trading and caps, carbon taxes, biomass fuel use, green purchasing, and green building. The data can be effective at establishing performance of MDF in comparison to other materials by conducting life-cycle assessments with output measures in terms of impacts on human health, environment, and resource use. Researchers have documented the favorable environmental performance of structural wood products for buildings; developing a database for MDF can serve a similar basis for establishing its favorable environmental performance.

Medium density fiberboard (MDF) is a non-structural panel product developed in the 1970s to utilize 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 landfill to dispose of them as waste material. Over the years the product has evolved into a highly engineered product designed to meet specific end-use requirements. MDF is an industrial type panel used for making furniture, cabinets, tables, countertops, and millwork. The production of MDF falls into the Standard Industrial Classification (SIC) Code 2493—reconstituted wood products—which includes other wood composite products such as hardboard, insulation board, particleboard, and oriented strand board (U.S. Census Bureau 2007). The six-digit Source Classification Code (SCC) for MDF production is 307009 (EPA 2007).

MDF is produced from industrial wood residues such as shavings, sawdust, ply trim, and chips, and can be produced from chips from logs or trees. The residues are refined to fibers or fiber bundles that are dried, blended with resin and wax, formed into a mat that is consolidated and cured under pressure and heat. MDF is produced in densities ranging from 31-50 lb/ft^3 (497-801 kg/m^3) to the material properties listed in the American National Standard ANSI A208.2-2002 (ANSI 2002). Production is measured on a thousand square foot (MSF) ¾-inch basis, which in SI units is equivalent to 1.7698 m^3. In 2004 the U.S. industry produced 3,091,848 m^3 and Canada produced 1,554,249 m^3 (CPA 2005). The survey for this study of the LCI of MDF production in the U.S. collected data from mills that produced 833,221 m^3 in 2004, representing 27% of total production in the U.S. The panels are produced in thicknesses ranging from 3/8 inch to 1-1/4 inch and in widths from 4 to 5 ft and lengths from 8 to 24 ft. Thin MDF, a subgroup of MDF product, of approximately 1/8-inch thickness (3 mm) was not included in this study.

The goal of this study was to document the life-cycle inventory (LCI) of manufacturing MDF panels based on industrial wood residues for the U.S. The study covers all environmental impacts from "in-ground" resources of wood, fuels, electricity, resin, wax and scavenger through manufacture of the MDF. This is referred to as a cradle-to-product gate study, see Figure 1.1. The manufacturing data were collected by survey of the industry, and the LCI data for the input wood residues were from data and analyses done in earlier CORRIM studies for the production of residues as co-products from plywood and lumber manufacture (Wilson and Sakimoto 2005, Milota et al. 2005). Also included from earlier CORRIM studies are the LCI of the forest resources, harvesting, and delivery impacts (Johnson et al. 2005). This study considers those impacts in the manufacture of MDF, documenting all inputs of materials, fuel, and electricity, and all outputs of product, co-product, and emissions to air, water and land. The boundary conditions are defined in Section 1.1.3. Primary data were collected by direct survey of MDF manufacturers. The survey questionnaire is included in Appendix 1 of this report. Supplemental secondary data were obtained for impacts associated with the manufacture, delivery, and consumption of electricity and all fuels (Franklin Associates 2004, PRé Consultants 2007, USDOE 2007), from another CORRIM study on the life-cycle inventory of urea-formaldehyde resin (Wilson 2009), and wax, urea scavenger and their input chemicals (Ecoinvent 2007) that were adjusted to U.S. energy values. The survey data represents MDF production in terms of input materials, electricity, and fuel use, and emissions for the 2004 production year. The four mills surveyed were selected to be representative of U.S. production practices.

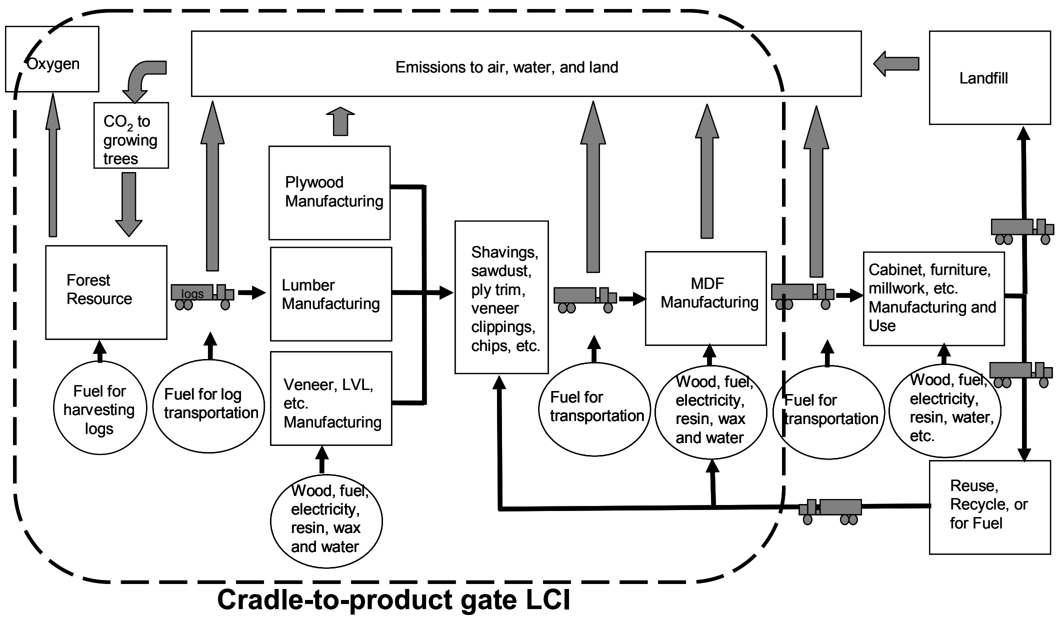


Figure 1.1. The life cycle of medium density fiberboard (MDF).

The life-cycle inventory study was conducted in accordance with the Consortium for Research on Renewable Industrial Materials (CORRIM) guidelines (CORRIM 2001) and ISO 14040 and 14044 protocol (ISO 2006a and ISO 2006b).

1.1.1 Survey Data Analysis

The survey data from the four mills were analyzed for quality by assessing for outliers, and conducting mass and energy balances. The data for each mill were converted to a unit of production basis, in this case 1.0 thousand square feet (MSF) ¾-inch thickness basis, to make the comparison. Any outliers were resolved by contacting the mills. A mass balance considering all inputs of materials—wood, resin, wax, and scavenger—and all outputs of product and emissions was 0.3% which is within the 5% balance requirement of the CORRIM guideline. Energy balances were done to determine the expected energy use to dry the desired amount of water from the wood fibers during processing. The average moisture content of wood material coming into the mill was 39% on an oven-dry weight basis and the targeted moisture content for the dried material with resin applied was 7-9%. Considering the energy use of the fuels and the amount of moisture removed, the energy use for drying per pound of water removed was 2,583 Btu (6.01 MJ/kg water) based on the fuel's higher heating value (HHV) and 2,109 Btu (4.91 MJ/kg water) on its lower heating value (LHV) which considers the effects of the combustion of the water in the fuel. The energy use was found to be as expected which would be approximately 2,000 Btu/lb of water dried based on LHV. The data for the mills were then weight-averaged based on the production of each mill and the total production. Only the weight-averaged data were presented in this report. The weight-averaged mill produced 117,699 MSF ¾-inch basis (208,305 m^3) annually of MDF at an average density of 46.3 lb/ft^3 (741 kg/m^3) oven dry. The data for all wood inputs and outputs were given as oven dry, whereas chemical inputs of resin, wax and scavenger were given at 100% solids although for reference their actual solids percentage as used in the mill are stated.

1.1.2 Manufacturing Process

The MDF manufacturing process is highly automated, process-controlled and fairly linear. The process is shown in Figure 1.2.

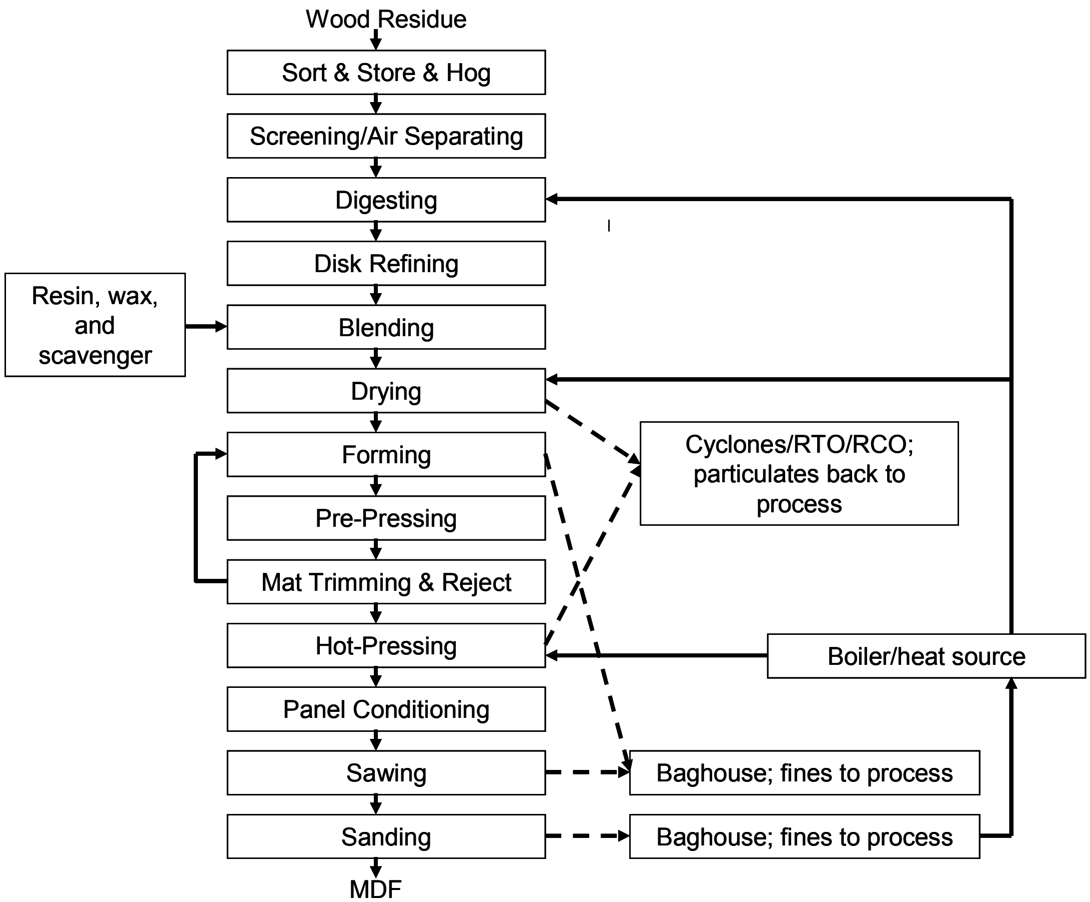


Figure 1.2. On-site process flow for the production of MDF.

The process consists of the following steps:

Sort and store—wood residue is delivered to the mill normally by truck; the residue, referred to in the industry as *furnish*, consists of shavings, sawdust, ply trim, and chips of various moisture contents; the residue is stored under cover; the moisture content of the residue can range from 10 to 100% on an oven-dry weight-basis. Sometimes a hog is used to reduce residue size.
Digesting—the wood residue is placed in a pressurized vessel called a digester to *cook* the wood in preparation for refining into fibers. The wood is cooked with steam at pressure to soften the lignin binder 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 which separate the fibers at the lignin binder; this process is usually accomplished with the use of pressurized disk refiners—a method for mechanically reducing wood into its individual fibers.

Blending—a process whereby resin, wax, catalyst, and scavenger are distributed onto the fibers. Friction and contact between fibers may help to distribute the resin. The resin most used is urea-formaldehyde (UF), however some products are made with either melamine-urea-formaldehyde or polymeric isocyanate resins for those products where moisture resistance is desired. The resin and other additives can be applied to the fiber in the refiner, coming out of the refiner in the blow line, or in the dryer flash tube prior to 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 moisture contents than the 39% average residue entering the mill as a result of steam treating in the digester, and are dried to a targeted moisture content 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 to dry. As wood dries at elevated air temperatures of up to 500^{o}F (260^{o}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 desire panel properties and efficiency.

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; presses operate at sufficient temperature of about 340^{o}F (170^{o}C) and duration to cure the resin, and sufficient pressure of about 750 psi (5.17 MPa) to consolidate the mat to a desired density of 31-50 lb/ft^3 (497- 801 kg/m^3); the physical properties of the panel are controlled during pressing. 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 a cooling wheel to enable the temperature of the panels to drop below a value where the UF resin will 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 put back into residue prior to the blending process or used as fuel for the dryers.

Sawing—relatively large panels are sawn to dimensions of panel widths of 4 or 5 ft and lengths of 8 or 9 ft or even longer lengths. Panel trim is hammermilled into particles and sent back into the process prior to the former.

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). The boilers are generally fired with wood residue, natural gas, or oil fuels; with this combustion, air emissions of CO_2, CO and others are generated. The emission control devices are used to reduce particulate and chemical emissions. Of significance is the large quantity of natural gas and electricity used to operate the RTO and RCO devices, and similarly large quantities of electricity to operate BF systems. Only one of the four mills used a combination of cyclones and RCO/RTO devices to reduce particulates, VOC and HAP emission levels.

Implementation of the Plywood and Composite Wood Products Maximum Achievable Control Technology (PCWP MACT) (EPA 2004) rule after the low risk emissions subcategory was delisted by the courts, will in October 2007 necessitate that all MDF plants that cannot meet its emissions averaging, work practice standards or production-based limits will 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 electricity for their operation and in turn increased emissions related to the combustion of fossil fuels.[2]

1.1.3 Functional Unit

For the life-cycle inventory all material flows, fuels and electricity, as well as product, co-product and emissions are normalized to the functional unit of 1.0 MSF (thousand square feet) ¾-inch basis and 1.0 m^3 of MDF panel.

1.1.4 System Boundary Conditions

A black-box approach was selected for modeling the life-cycle inventory 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 since unlike those processes that have a higher percentage of co-product that are generated at various steps throughout the manufacturing process, MDF production has little if any co-products. In a black box approach all input flows into the box and all output flows out of the box—see Figure 1.3. For on-site emissions only those inputs and outputs directly associated with the manufacturing process are considered—those emissions that occur due to on-site combustion of fuels whether for process heat or operating equipment, and those as a result of processing the wood are considered. The life-cycle inventory for on-site emissions is referred to as a product gate-to-gate inventory. For the cumulative or total emissions, in this case referred to as cradle-to-product gate emissions, it considers all impacts including those for the manufacture and delivery of wood residue, fuels, electricity, wax, and scavenger back to their in-ground resource. This cumulative system boundary provides the cradle-to-product gate impact from the forest and raw resources in the ground through all co-product and product processing steps. Only a small amount—0.3%—of co-product was produced during MDF manufacture as wood fuel sold to other manufacturers, the amount is insignificant, as such no environmental burden was assigned to it. Also sold was some bark mulch, it was not assigned any burdens in accordance with the CORRIM guidelines (CORRIM 2001).

---

[2] To reduce VOC and HAP emissions, RTOs use large amounts of natural gas to combust the emissions, and large amounts of electricity to operate fans to transport the emissions; RCOs use a combination of a catalytic converter and the combustion of natural gas as well as electricity to operate the fans, and BFs use bio-organisms to convert emissions and electricity to operate fans (no natural gas is needed, however electricity use can be as great or greater than to operate a RCO or RTO).

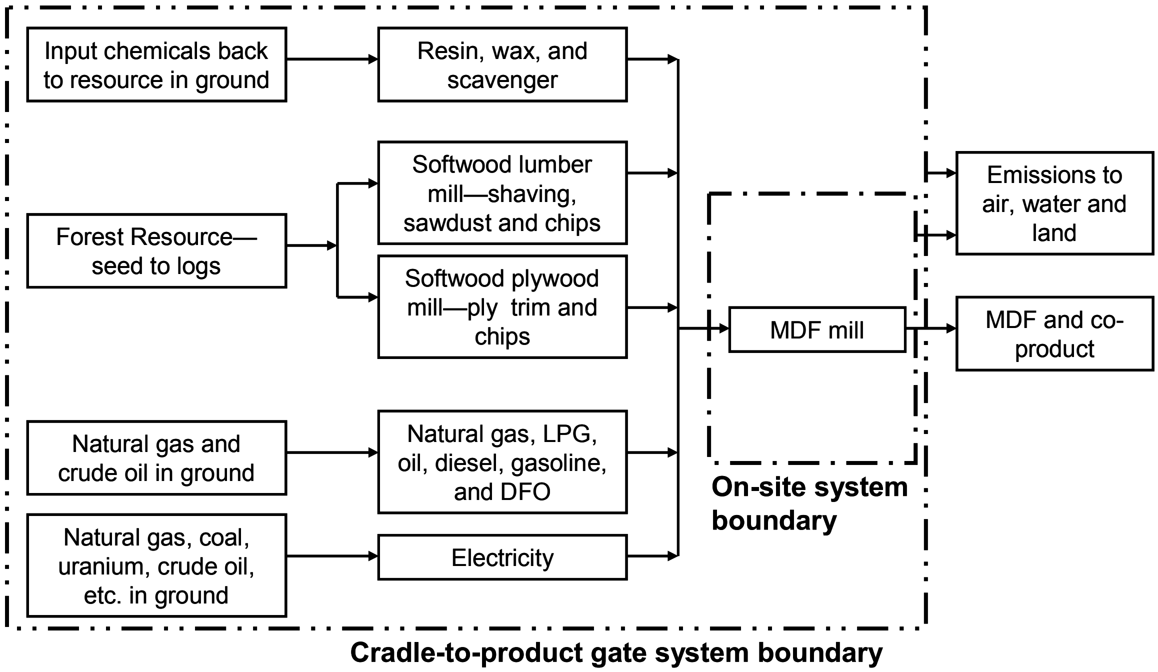


Figure 1.3. System boundaries for both on-site and cradle-to-product gate impact analyses.

1.1.5 Materials Flow

Those materials considered in the LCI analysis included those listed in Table 1.1. Input materials considered were wood residues, urea-formaldehyde (UF) resin, emulsion 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 melamine urea formaldehyde (MUF) and polymeric isocyanate (pMDI). The life-cycle inventory data of this study are only for UF resin bonded MDF which represents 98% of panels produced in the survey. Although the non-wood 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 the remaining percentage as water. The urea scavenger is used to "capture" excess formaldehyde to reduce its emission from the panel. The wood residue is representative of the wood species used to produce lumber and plywood in the major production centers of the U.S., which includes softwoods for the southeast and Pacific Northwest regions, and hardwoods for the northeast and northcentral regions.

Table 1.1. Listing of input materials and product for manufacturing MDF.

Input Materials	Products
Wood residue	MDF
Green chips (51%)[1]	
Green sawdust (51%)[1]	
Green shavings (48%)[1]	
Dry shavings (11%)[1]	
Plywood trim (8%)[1]	
Urea-formaldehyde resin (62%)[2]	
Wax (58%)[2]	
Urea scavenger (40%)[2]	

[1] Average moisture content on oven-dry basis as input to mill.

[2] Solids content as input to mill.

The finished MDF has an oven-dry weight of 2,893 lb/MSF ¾-inch basis (741 kg/m^3), consisting primarily of wood residue 2,577 lb/MSF (660 kg/m^3) and 292 lb/MSF (75 kg/m^3) of urea-formaldehyde resin. The wood component represents 89% and the resin 10.1% of the total board weight, lesser amounts of wax and urea scavenger make up the remainder of the board weight. The board weight and its components are less than the inputs since some material is lost during processing primarily as a result of the sanding operation. A listing of the various board components and their weights are given in Table 1.2.

Table 1.2. Listing of components in MDF panel.

Panel[1]	**lb/MSF**	**kg/m^3**	**%**
MDF	2,893	741	100
Panel components[1]			
Wood residue	2,577	660	89.1
Urea-formaldehyde resin	292	75	10.1
Wax	18	4.7	0.6
Urea scavenger	4.5	1.1	0.2

[1] Oven-dry and 100% solids weights of panel and components.

1.1.6 Transportation

The delivery of materials to the mills is by truck although some resin is delivered by pipeline from adjacent resin plants. Table 1.3 gives the one-way deliver distances for the material inputs. Usually these deliveries have no back haul of other materials.

Table 1.3. One-way delivery distance by truck for input materials to MDF mills.

Material	Delivery Distance	
	mile	km
Wood residue	100	161
Bark hog fuel	52	84
Urea-formaldehyde resin	83	134
Wax	83	134
Urea scavenger	83	134

1.1.7 Assumptions

The data collection, analysis, and assumptions followed protocol as defined in Consortium for Research on Renewable Industrial Materials (CORRIM)—Research Guideline for Life Cycle Inventories (CORRIM 2001) and the ISO 14040 and 14044 standards for environmental management and documentation (ISO 2006a and 2006b). The environmental impact analysis was done with SimaPro 7.1 software which was developed in the Netherlands and has a Franklin Associates (FAL) database to provide impacts for fuels and electricity for the U.S (PRé Consultants 2007). For materials not covered in the FAL database, the Ecoinvent v1.0 database, a comprehensive database for Europe, was used to determine environmental impacts; to adjust chemicals from the Ecoinvent database to the U.S. analysis, fuels and electricity within the database were converted to FAL processes (Ecoinvent 2004). Additional conditions include:

- All data from the survey were weight averaged for the four mills based on production in comparison to their total production for the year. Where appropriate, missing data from various mills were not included in weight averages.
- All environmental burdens were assigned to the MDF.
- A black-box approach was used to model the MDF process since the percentage of co-product was very small (0.3%) and the approach does not impact the accuracy of assigning the burdens.
- Environmental impacts were assessed for MDF manufacturing cradle-to-product gate that included all impacts from in-ground resources through the production of wood residue, resin, wax, scavenger, electricity and fuels. The life-cycle data for the wood residue consisting of shavings, sawdust, chips, plywood trim and fines were determined for earlier CORRIM LCI studies of softwood lumber, plywood, and other primary wood products.
- To determine energy content of fuels, their higher heating value (HHV) was used. The HHV is defined as the amount of heat released by a fuel initially at 25^oC when it is combusted and the products have returned to their initial temperature. For wood it is the maximum achievable energy value for oven dry wood. In contrast, the lower heating value (LHV) is determined when the cooling is stopped at 150^oC and only some of the reaction energy is recovered. The HHV provides a fuel's intrinsic property whereas the LHV is used as a practical number. It is important to state the fuel content value for comparison to other data.
- Site emissions of carbon dioxide (CO_2) for both biogenic and fossil sources were not reported in the surveys; therefore the values were determined using the Franklin Associates' database for the combustion of the various fuels. Other emissions calculated in this manner included carbon monoxide (CO) and methane (CH_4).
- Carbon dioxide was tracked separately through the processes as "biogenic" for the combustion of wood fuels whether they are bark, sander dust, waste or hogged fuel, and as "fossil" for the combustion of fossil fuels such as oil, coal, natural gas and propane. The U.S. Environmental Protection Agency (EPA) considers CO_2 biogenic as global-warming-impact neutral because the

CO_2 can be removed from the atmosphere by the growing of trees that absorb it, breaking it down into carbon to form wood substance and releasing oxygen back to the atmosphere (USEPA 2003).

- Unaccounted wood mass between input and output material flows in the production of MDF based on survey data were found to be 0.3% which is within the maximum 5% condition specified in the CORRIM protocol.

1.2 Product yields

The inputs to produce 1.0 MSF ¾-inch basis consist of 3,094 lb (793 kg/m^3) of industrial wood residue on an oven-dry weight basis that was produced as co-product in the manufacture of lumber, plywood, and other primary wood products. See Table 1.4 for all inputs and outputs for the manufacture of MDF. These inputs yielded 2,893 lb/MSF (741 kg/m^3) of MDF comprised of wood, resin, wax, and scavenger. A small amount of bark mulch (12.9 kg/m^3) and a very small amount of wood fuel (0.06 kg/m^3) was produced in the process and sold outside of the system boundary. Also a small amount of wood waste (2.21 kg/m^3) and boiler fly ash (1.94 kg/m^3) was sent to the landfill. There was also some wood residue fuel generated internally in the manufacturing process—273 lb (70 kg/m^3) of sander dust that was burned in the fiber dryers and 211 lb (54 kg/m^3) of wood waste that was burned in either the dryer or boiler. Also purchased was 919lb (236 kg/m^3) of bark hog fuel that was used to provide process heat.

Table 1.4. Inputs and outputs for the production of MDF.

INPUTS				
Materials	**Unit**	**Unit/MSF**	**SI Unit**	**SI Unit/m^3**
Wood residue[1]				
Green chips	lb	1,666	kg	427
Green shavings	lb	240	kg	62
Dry shavings	lb	489	kg	125
Green sawdust	lb	590	kg	151
Plywood trim	lb	109	kg	28
Total wood furnish	lb	3,094	kg	793
Urea-formaldehyde resin[2]	lb	325	kg	83.3
Wax[2]	lb	20.3	kg	5.21
Urea scavenger[2]	lb	4.23	kg	1.28
Electricity				
Electricity	kWh	734	MJ	1494
Fuels[1]				
Natural gas	ft^3	2,699	m^3	43
Diesel	gal	0.20	liter	0.43
LPG	gal	0.35	liter	0.76
Gasoline and kerosene	gal	0.06	liter	0.13
Distillate fuel oil	gal	0.13	liter	0.27
Sander dust (wood)	lb	273	kg	70
In-mill generated wood hog fuel	lb	211	kg	54
Bark hog fuel purchased	lb	919	kg	236
In-mill dirty fuel from chip wash	lb	10.6	kg	2.72
Water Use				
Municipal water	gal	437	liter	935
Well water	gal	211	liter	452
OUTPUTS[1,3]				
Medium density fiberboard (MDF)	lb	2,891	kg	741
Bark mulch (sold)	lb	50.3	kg	12.9
Wood boiler fuel (sold)	lb	0.24	kg	0.06
Wood waste to landfill	lb	8.62	kg	2.21
Boiler fly ash to landfill	lb	7.57	kg	1.94

[1] All wood and bark weights given as oven dry.

[2] Weight at 100% solids; solids content as received at mill are UF resin 62%, wax 58%, and scavenger 40%.

[3] Emissions to air and water listed in separate table.

The mass balance found from the survey that in terms of input and output wood materials, it differed by 0.3%, with slightly more wood going out than coming in, see Table 1.5. This difference is within the acceptable 5% limit of the CORRIM protocol.

Table 1.5. Wood mass balance for MDF production.

Inputs[1]	lb/MSF	kg/m^3
Green chips	1,666	427
Green shavings	240	62
Dry shavings	489	125
Green sawdust	590	151
Plywood trim	109	28
Bark hog fuel purchased	919	236
Bark hog fuel[2]	(919)	(236)
Sander dust for fuel[2,3]	(245)	(63)
In-mill generated wood hog fuel[2]	(211)	(54)
In-mill dirty fuel from chip wash[2]	(11)	(3)
Total	2,627	673
Outputs[1]		
MDF (wood only)[3]	2,576	660
Bark mulch sold	50	13
Wood boiler fuel sold	0.24	0.06
Wood waste landfill	8.6	2.2
Total	2,635	675
Outputs-inputs difference %	0.3	0.3

[1] Oven-dry weights.

[2] Used in the mill as fuel.

[3] Wood only, excludes resin, wax, and scavenger.

1.3 manufacturing energy summary

1.3.1 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 (LPG), 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 that with further installation of emissions control systems to meet PCWP MACT (USEPA 2004) regulations there will be increased use of natural gas and electricity to operate these systems, resulting in increases of CO_2 fossil emissions. The electricity is used to operate equipment within the plant, equipment such as conveyors, refiners, fan motors, hydraulic press motors, sanders, and emission control systems. Electricity is used throughout the process. The fuels for equipment are used for loaders and forklifts, and the natural gas and wood fuels are used to operate flash tube dryers and heat presses.

1.3.2 Electricity Use Summary

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 734 kWh/MSF (1,494 MJ/m^3), see Table 1.4. The breakdown of fuel source to generate the electricity was based on the U.S. average as given by the U.S. Energy Information Agency (EIA 2007) for

2004. Table 1.6 gives a breakdown of the electricity generation by fuel source. The dominant fuel source is coal at 49.8%, followed by nuclear at 19.9% and natural gas at 17.9%. The less contributing sources are hydroelectric at 6.8%, petroleum at 3.0% and other renewables at 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 life-cycle inventory since 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. In PRé Consultant's SimaPro environmental assessment software, no impacts are associated with hydro-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.

Table 1.6. U.S. electricity data by fuel source for 2004 (EIA 2007).

Fuel source	%
Coal	49.8
Petroleum	3.0
Natural gas	17.9
Other gases	0.4
Nuclear	19.9
Hydroelectric	6.8
Other renewables	2.3
Pumped storage	(0.2)
Other	0.2
Total electricity industry	100

1.4 Fuel Use As a Heat Source

Wood fuel, whether hog, waste or bark fuel, is the primary fuel used in the MDF process; it is used for providing process heat for digesting, drying wood residue and heating steam or oil for hot pressing. Wood is used for fuel in the form of sander dust that is generated in the process when the panel is 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. And two mills purchased bark hog fuel for use in processing. The second largest fuel source is natural gas which is used for dryers, and one of the four mills reported using emissions control devices (RTO/RCO) which use natural gas for their operation. With implementation of PCWP MACT (USEPA 2004) mills that cannot meet its emissions averaging, work practice standards or production-based limits will have some type of emission control system installed to meet regulations. The mill that reported use of a VOC and HAP control system used both a regenerative catalytic oxidizer (RCO) and a regenerative thermal oxidizer (RTO) for controlling emissions from the dryers and press. Both systems have an efficiency of 90% or better for reducing HAPs. 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 fork lift trucks and handlers within the mill. Table 1.7 gives the fuel use on-site energy for manufacturing MDF. The total fuel use for process heat is 15,413,913 Btu/MSF (9,188 MJ/m^3) of which 82% is generated through the combustion of wood fuel, a sustainable resource as opposed to using oil and natural gas fuels that are not sustainable, and the other 18% is from natural gas. In terms of the total energy 17,987,477

Btu/MSF (10,723 MJ/m^3), which includes fuel for process heat and equipment, and includes electricity, the wood fuel energy represents 70%, natural gas energy 15%, and the electricity energy 14%. The non-wood energy component represents an opportunity for improving sustainability by substituting for it with sustainable wood fuel.

Table 1.7. On-site fuel, electricity, and energy1 use in the manufacture of MDF.

Fuel for process heat	Unit	Unit/MSF	Btu/MSF	SI Unit	SI Unit/m^3	MJ/m^3	%
Natural gas	ft^3	2,699	2,779,728	m^3	43	1,657	
Sander dust	lb	273	2,458,114	kg	70	1,465	
In-mill generated hog fuel	lb	209	1,885,084	kg	54	1,124	
Bark hog fuel purchased	lb	919	8,273,310	kg	236	4,932	
Distillate fuel oil (DFO)	gal	0.13	17,677	liter	0.27	11	
Subtotal			15,413,913			9,188	85.7
Fuel for equipment							
Diesel	gal	0.20	27,750	liter	0.43	17	
LPG	gal	0.35	33,690	liter	0.75	20	
Gasoline and kerosene	gal	0.06	7,717	liter	0.13	5	
Subtotal			69,157			41	0.4
Electricity							
Electricity purchased	kWh	734	2,504,408	MJ	1,493	1,493	13.9
Total energy			17,987,477			10,723	100

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

1.5 Mill Emissions for Producing MDF

Outputs for the production of MDF include a very small quantity of wood fuel sold outside of the system boundary (this was not assigned an environmental impact because of its small contribution of only 0.3%), some bark mulch that was given away free (this was not assigned an environmental impact in accordance with CORRIM protocol), and there were emissions to air, water and land, see Table 1.8. Emissions are generated due to the mechanical processing which 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 due to the combustion of fuels such as wood, natural gas, and propane. Emissions to air include particulate and particulate PM10 (less than 10 μm in size) 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, while no mills reported acrolein, 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 individual HAPs are identified in the table as (HAP) and the greenhouse gases as (GHG). The CO_2 for both the biogenic (wood) and fossil fuel sources, and the methane, which were not reported in the survey, were determined by entering the actual fuel use for both heat sources and equipment into the SimaPro software; then using the Franklin Associates database for U.S. fuels (FAL 2004), the carbon dioxide and methane values were determined. The CO_2 for both the biogenic (wood) and fossil fuel sources were tracked separately. The CO_2 from biogenic combustion sources is not considered a greenhouse gas according to the U.S. Environmental Protection Agency—it does not contribute to global warming because of it has a closed loop life cycle where it is re-absorbed by the growing of trees, releasing oxygen to the atmosphere and taking the carbon to make more wood (USEPA 2003). The carbon monoxide although provided in the survey was also calculated in the same manner to include other sources such as fuel combustion emissions for fork lifts that are not included in survey data, the calculated CO value was slightly larger than the survey value.

Table 1.8. On-site reported outputs for the production of 1.0 MSF ¾-inch basis and 1.0 m3 of MDF.

Product	**lb/MSF**	**kg/m³**
MDF	2,893	741
Emissions to air[1]	**lb/MSF**	**kg/m³**
Carbon dioxide, biogenic[2]	2973	762
Carbon dioxide, fossil (GHG)[2,3]	325	83.4
Carbon monoxide[2]	19.7	5.04
Methane (GHG)[2]	0.009	0.002
Nitrogen oxides	1.48	0.38
Sulfur oxides	0.028	0.007
Total VOC	3.28	0.84
Particulate	1.42	0.36
Particulate (PM10)	1.13	0.29
Acetaldehyde (HAP)[3]	NR[4]	NR
Acrolein (HAP)	NR	NR
Formaldehyde (HAP)	0.62	0.16
Methanol (HAP)	0.86	0.22
Phenol (HAP)	NR	NR
HAPs	NR	NR
Emissions to water[1]	**lb/MSF**	**kg/m³**
Suspended solids	0.039	0.010
BOD	0.028	0.007
Ammonia nitrogen	0.009	0.002
Emissions to land[1]	**lb/MSF**	**kg/m³**
Boiler fly ash	7.59	1.94
Wood waste landfill	8.63	2.21

[1] Emissions data reported from surveys.

[2] Emissions determined by output from fuel entries into SimaPro for site emissions.

[3] (HAP) is hazardous air pollutant and (GHG) are greenhouse gases.

[4] NR not reported

1.6 Cradle-to-product Gate Process Related Resource Use and Emissions

The life-cycle inventory for the production of MDF covers its cycle from tree seed through the use of wood as a resource to the manufacture of MDF. It examines the use of all resources back to their source in the ground and all emissions to air, water and land. Table 1.9 gives the raw materials, energy, and emissions for the cradle-to-product gate inventory to produce 1.0 m³ of MDF. The raw materials in the ground include coal, natural gas, limestone, crude oil, and uranium, and include water usage. Materials of small quantities of 1.0E-02 kg/m³ and less are not included in the listing. Because life-cycle studies involve tracing resource use back to its in-ground source, some materials or substances can involve many steps of backtracking, which 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. The filter varied depending on whether the emission was to air, water, or land. The exception was for substances that are highly toxic such as mercury where values are less than the cut-off criteria value were recorded.

For record keeping only, wood used for fuel is listed although not a true raw material in the sense its origin is a tree seed. Some sources of energy or fuels cannot be traced back to their original resource in the ground. Such energies include "energy from hydro power," "electricity from other gases" which source is unknown, and "electricity from renewables" which 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 listed in Table 1.9 also. The emissions to air and water used a cut-off value of 1.0E-04 kg/m^3, and to land used a cut-off of 1.0E-02 kg/m^3, waste of 2.0E-01 kg/m^3, and radiation terms used a cut-off of 1.0E+04 Bq/m^3. Some emissions because of their toxicity, even though in quantities below the cut-off, are recorded. The greenhouse gases (GHG) and the HAPs associated with the production of wood products are identified. Raw materials and emissions for a cradle-to-product gate inventory are greater than those resources and emissions that occur at the production site, this is true for all processes. The difference between on-site and cradle-to-gate resource use can be found by comparing Tables 1.7 and 1.8 with 1.9.

Of significance is the raw material source of "carbon dioxide in air" which accounts for the uptake of CO_2 during the growing of trees. About half the mass of wood and bark is carbon; to determine the equivalent of carbon dioxide (CO_2) that was removed from the air to form this carbon (C) in wood and bark, multiply the wood carbon content in kg by 3.67 kg CO_2/kg which is the molar mass ratio of CO_2 to C of 44 to 12. To produce 1.0 m^3 of MDF from seed to product the "carbon dioxide in air" total uptake for wood residue and wood fuel is 2,088 kg which can be used to offset the CO_2 emissions from wood and fossil fuel use and some CO_2 in the atmosphere. The breakdown of the CO_2 uptake by contributor is 1,268 kg for the CO_2 equivalent 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. The 1,268 kg CO2 equivalent store in MDF is more than sufficient to offset all greenhouse gas emissions from cradle-to-gate with remaining store to offset additional greenhouse gases emitted as a result of MDF's delivery, use and disposal, and even offset some CO2 in the atmosphere; which reduces its impact upon global warming. This carbon storage 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 a 100 years.

Table 1.9. SimaPro output of cumulative emissions cradle-to-product gate for the production of MDF.

Raw Materials	lb/MSF	kg/m^3
Calcite in ground	5.37E-01	1.38E-01
Carbon dioxide in air[1]	8.15E+03	2.09E+03
Clay in ground	1.54E-01	3.94E-02
Coal in ground	4.66E+02	1.19E+02
Crude oil in ground	1.73E+02	4.44E+01
Gravel in ground	4.51E+00	1.16E+00
Iron ore in ground	4.98E-02	1.28E-02
Limestone in ground	8.03E+01	2.06E+01
Natural gas in ground	4.80E+02	1.23E+02
Nickel in ground	1.40E-01	3.58E-02
Sodium chloride in ground	2.51E-01	6.44E-02
Uranium in ground	2.03E-03	5.20E-04
Water unspecified natural origin	6.19E+03	1.59E+03
Water well in ground	2.40E+03	6.15E+02
Wood fuel	1.53E+03	3.92E+02

Energy	kWh/MSF	MJ/m^3
Energy from hydro power	1.31E+02	2.10E+02
Electricity from other gases	3.01E+00	6.43E+00
Electricity from other renewables	2.31E+03	3.70E+01

Emissions to air[2]	lb/MSF	kg/m^3
Acetaldehyde (H)	2.31E-03	5.92E-04
Acetic acid	2.58E-03	6.60E-04
Acetone	9.73E-04	2.49E-04
Acrolein (H)	1.72E-05	4.41E-06
Aldehydes, unspecified	4.69E-02	1.20E-02
Alpha-pinene	9.05E-03	2.32E-03
Aluminum	2.44E-03	6.24E-04
Ammonia	8.78E-01	2.25E-01
Arsenic	2.19E-04	5.60E-05
Barium	6.70E-03	1.72E-03
Benzene	8.39E-03	2.15E-03
Beta-pinene	3.51E-03	9.00E-04
Butane	5.05E-03	1.30E-03
Carbon dioxide, biogenic	3.20E+03	8.20E+02
Carbon dioxide, fossil (GHG)	2.29E+03	5.86E+02
Carbon disulfide	1.02E-03	2.61E-04
Carbon monoxide	2.56E+01	6.55E+00
Chlorine	1.20E-02	3.06E-03
Dinitrogen monoxide (GHG)	1.44E-02	3.70E-03
Formaldehyde	6.52E-01	1.67E-01
HAPS	1.48E+00	3.80E-01
Hydrocarbons, unspecified	1.94E-02	4.97E-03
Hydrogen chloride	8.74E-02	2.24E-02
Iron	7.15E-03	1.83E-03
Manganese	1.38E-02	3.55E-03
Mercury	3.55E-05	9.10E-06
Metals, unspecified	2.96E-04	7.59E-05
Methane (GHG)	5.30E+00	1.36E+00
Methanol (H)	9.61E-01	2.46E-01
Nitrogen oxides	1.27E+01	3.26E+00
Nitrous oxide (GHG)	9.99E-03	2.56E-03
NMVOC, non-methane	5.79E+00	1.48E+00
Organic substances, unspecified	9.09E-01	2.33E-01
Particulates	1.50E+00	3.85E-01
Particulates (unspecified)	5.86E-02	1.50E-02
Particulates, < 10 um	3.18E+00	8.16E-01
Particulates, < 2.5 um	2.94E-01	7.54E-02
Particulates, > 10 um	2.29E-01	5.88E-02
Particulates, > 2.5 um, < 10um	1.17E-01	3.00E-02
Particulates, unspecified	1.22E+00	3.13E-01
Pentane	8.66E-03	2.22E-03
Phenol (H)	7.52E-03	1.93E-03
Potassium	1.19E+00	3.05E-01
Sodium	2.93E-02	7.51E-03
Sulfur dioxide	1.98E-01	5.09E-02
Sulfur oxides	2.41E+01	6.17E+00
Toluene	1.52E-03	3.88E-04
Vanadium	6.49E-03	1.66E-03
VOC	3.64E+00	9.32E-01
Zinc	6.83E-03	1.75E-03

	Bq/m^3
Noble gases, radioactive, unspec.	3.59E+04
Radioactive species, unspecified	5.77E+06
Radon-222	6.95E+04

Emissions to water	lb/MSF	kg/m^3
Aluminum	3.35E-03	8.58E-04
Ammonia	1.31E-03	3.36E-04
Ammonium, ion	9.11E-02	2.34E-02
BOD5	6.23E-02	1.60E-02
Boron	4.48E-02	1.15E-02
Cadmium, ion	1.16E-03	2.97E-04
Calcium, ion	2.34E-02	5.99E-03
Chloride	1.21E+00	3.09E-01
Chromium	1.18E-03	3.02E-04
COD	4.15E-01	1.06E-01
DOC	4.76E-02	1.22E-02
Fluoride	5.07E-02	1.30E-02
Formaldehyde	1.63E-02	4.17E-03
Iron	6.37E-02	1.63E-02
Iron, ion	3.76E-03	9.62E-04
Lead	6.15E-05	1.58E-05
Magnesium	8.48E-04	2.17E-04
Manganese	3.65E-02	9.36E-03
Mercury	3.55E-05	9.10E-06
Metallic ions, unspecified	3.84E-03	9.83E-04
Methanol	4.88E-03	1.25E-03
Nickel, ion	7.72E-04	1.98E-04
Nitrate	4.57E-04	1.17E-04
Nitrogen	3.08E-02	7.88E-03
Nitrogen, organic bound	4.99E-04	1.28E-04
Oils, unspecified	4.52E-01	1.16E-01
Organic substances, unspecified	8.10E-02	2.08E-02
Phenol	1.64E-03	4.21E-04
Phosphate	4.25E-02	1.09E-02
Phosphorus	1.63E-03	4.17E-04
Potassium, ion	4.41E-04	1.13E-04
Silicon	1.83E-01	4.69E-02
Sodium, ion	1.67E-02	4.29E-03

Emissions to water (cont.)	lb/MSF	kg/m³
Solids, inorganic	8.60E-04	2.20E-04
Solved solids	2.55E+01	6.53E+00
Sulfate	1.17E+00	3.01E-01
Sulfuric acid	1.12E-02	2.87E-03
Suspended solids	3.94E-02	1.01E-02
Suspended solids, unspecified	1.07E+00	2.75E-01
TOC, Total Organic Carbon	4.76E-02	1.22E-02
Zinc, ion	5.18E-04	1.33E-04

Waste	lb/MSF	kg/m³
Packaging waste, paper & board	1.10E+00	2.83E-01
Waste, inorganic	1.86E+00	4.76E-01
Waste, solid	2.65E+02	6.79E+01
Wood waste	6.49E-01	1.66E-01

Emissions to land	lb/MSF	kg/m³
Boiler fly ash	7.57E+00	1.94E+00
Wood waste	8.62E+00	2.21E+00

[1] Includes CO_2 uptake for carbon store in wood component of panel (1,268 kg) and in wood fuel (820 kg).

[2] (HAP) is hazardous air pollutant common to wood products industry and (GHG) are greenhouse gases.

1.7 Cradle-to-product gate resource use for embodied energy

The embodied energy to produce MDF can be given in several manners. 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.

Table 1.10 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 higher heating values (HHV) of the fuels. Wood fuel use provides 39.6% of the energy, followed by natural gas at 32.3%, coal at 15.1% and oil at 10.8%, all other sources are of minor significance. 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 non-renewable 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.

Table 1.10. A breakdown by fuel source to produce MDF cradle-to-product gate.

Substance	Btu/MSF	MJ/m^3	%
Coal in ground	5,238,855	3,123	15.1
Natural gas in ground	11,216,998	6,686	32.3
Crude oil in ground	3,763,238	2,243	10.8
Uranium in ground	332,230	198	1.0
Wood and bark fuel[2]	13,764,333	8,204	39.6
Electricity from other gases	10,794	6	0.0
Electricity from other renewables	62,068	37	0.2
Energy from hydro power	352,527	210	1.0
Total	34,741,042	20,707	100

[1] Energy values based on their higher heating values (HHV) of Table 1.7, uranium at 381,000 MJ/kg, and electricity at 3.6 MJ/kWh .

[2] Includes all sander dust, self-generated hog, purchased, and direct-fired wood fuels.

Energy contribution by the input component can be valuable in assessing the major contributors and for identifying opportunities for reducing energy use. Table 1.11 gives the embodied energy breakdown for manufacturing MDF from tree seed to product at the output gate of the mill. The total energy is 20,707 MJ/m^3 with the wood fuel, electricity, and UF resin making the major contributions of 37.3%, 21.8%, and 18.9%, respectively, followed by natural gas and wood residue at 10.7% and 8.1%, respectively; all other contributors of lesser significance. Transportation of wood, 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 consisting of shavings, sawdust, ply trim, and chips, and the urea-formaldehyde resin, wax and scavenger. Energy to provide manufacturing process heat and electricity represents 69% of the total.

Table 1.11. A breakdown of energy contributors to produce MDF cradle-to-product gate (based on higher heating values of fuels).

Process component	Btu/MSF	MJ/m^3	%
Wood residue	2,823,719	1,683	8.1
UF resin	6,582,711	3,924	18.9
Wax	446,511	266	1.3
Urea scavenger	54,573	33	0.2
Transportation diesel	538,806	321	1.6
Natural gas	3,700,620	2,206	10.7
Wood fuel	12,947,898	7,718	37.3
DFO fuel	20,778	12	0.1
Electricity	7,580,533	4,519	21.8
Diesel & other equipment fuels	41,214	25	0.1
Total	34,737,362	20,707	100

1.8 Sensitivity Analysis

The sensitivity analysis involves 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 carbon dioxide (fossil) emission. The magnitude of the impact is dependent on the input parameter and also on the output parameter of interest. For example, if the interest is the impact on the embodied energy of the product, Table 1.11 shows that the dominant contributors are the wood fuel (37.3%) followed by electricity (21.8%) and UF resin (18.9%), and to a lesser extent by natural gas use (10.7%) and wood residue (8.1%). Other contributors are of lesser significance. Therefore, changing the dominant parameters will have a significant impact on the total embodied energy whereas changes of other parameters such as wax, scavenger, transportation fuel, forklift fuel and boiler DFO fuel will have little if any impact. The embodied energy and its source of fuel can also impact resource use and emissions. Another way to examine this impact is to look at the list of raw materials in-ground and the air emissions in terms of their process contributor, see Table 1.12. For example, electricity use greatly impacts the use of raw materials such as coal and uranium, and emissions of acrolein, CO_2 fossil, mercury, and methane. Whereas the use of UF resin impacts the use of natural gas, crude oil and water, and emissions of NMVOC.

Table 1.12. Contribution by input parameter to the use of raw materials and air emissions for the manufacture of MDF.

									Boiler and dryer fuel			
			MDF proc.	Wood furnish	UF resin	Wax	Urea scav.	Transport.	Nat. gas	Wood	DFO	Electricity
Raw Materials	**lb/MSF**	**kg/m^3**	%	%	%	%	%	%	%	%	%	%
Calcite in ground	0.54	0.14	0	0	99	0	1	0	0	0	0	0
Carbon dioxide in air	8,147	2,088	20	80	0	0	0	0	0	0	0	0
Clay in ground	0.15	0.04	0	0	99	0	1	0	0	0	0	0
Coal in ground	466	119	0	5	7	0	0	0	0	0	0	88
Crude oil in ground	192	49	0	22	43	1	1	15	1	4	1	12
Gravel in ground	4.51	1.16	0	0	99	0	1	0	0	0	0	0
Iron ore in ground	0.05	0.01	0	100	0	0	0	0	0	0	0	0
Limestone in ground	80	21	0	2	2	0	0	0	0	67	0	29
Natural gas in ground	480	123	0	6	42	0	0	0	33	0	0	18
Nickel in ground	0.14	0.04	0	0	99	0	1	0	0	0	0	0
Sodium chloride in ground	0.25	0.06	0	0	100	0	0	0	0	0	0	0
Uranium in ground	0.002	0.001	0	5	7	0	0	0	0	1	0	86
Water, cooling, unspecified natural origin	1,804	462	0	0	75	25	0	0	0	0	0	0
Water, lake	32	8	0	0	100	0	0	0	0	0	0	0
Water, process and cooling, unspec.natural origin	42	11	0	100	0	0	0	0	0	0	0	0
Water, process, unspecified natural origin	241	62	0	0	91	7	2	0	0	0	0	0
Water, process, well, in ground	540	138	0	92	8	0	0	0	0	0	0	0
Water, river	87	22	0	0	100	0	0	0	0	0	0	0
Water, unspecified natural origin/m3	4,107	1,053	89	0	8	3	0	0	0	0	0	0
Water, well, in ground	1,860	477	95	1	4	0	0	0	0	0	0	0
Wood fuel	1,530	392	0	0	0	0	0	0	0	100	0	0
Emissions to air												
Acetaldehyde	2.31E-03	5.92E-04	0	83	16	0	0	0	0	0	0	0
Acrolein	1.72E-05	4.41E-06	0	7	7	0	0	0	0	0	0	85
Benzene	8.39E-03	2.15E-03	0	7	0	0	0	0	0	93	0	0
Carbon dioxide, biogenic	3.20E+03	8.20E+02	0	7	0	0	0	0	0	93	0	0
Carbon dioxide, fossil	2.29E+03	5.86E+02	0	9	20	1	0	4	16	0	0	50
Carbon monoxide	2.56E+01	6.55E+00	0	11	4	0	0	3	3	76	0	2
Formaldehyde	6.52E-01	1.67E-01	95	4	1	0	0	0	0	0	0	0
HAPS	1.48E+00	3.80E-01	100	0	0	0	0	0	0	0	0	0
Mercury	3.55E-05	9.10E-06	0	5	10	0	0	0	1	0	0	85
Methane	5.30E+00	1.36E+00	0	5	28	0	0	0	19	0	0	47
Methanol	9.61E-01	2.46E-01	89	2	9	0	0	0	0	0	0	0
Nitrogen oxides	1.27E+01	3.26E+00	0	17	14	0	0	6	9	19	0	33
NMVOC, non-methane	5.79E+00	1.48E+00	0	12	40	1	0	5	25	0	0	16
Particulates	1.50E+00	3.85E-01	94	6	0	0	0	0	0	0	0	0
Particulates, < 10 um	3.18E+00	8.16E-01	35	52	2	0	0	3	1	0	0	6
Phenol	7.52E-03	1.93E-03	35	52	2	0	0	3	1	0	0	6
Sulfur oxides	2.41E+01	6.17E+00	0	6	31	0	0	1	23	0	0	38
VOC, volatile organic compounds	3.61E+00	9.26E-01	91	9	0	0	0	0	0	0	0	0

An example of the sensitivity of the impact can be shown by changing the wood fuel and natural gas use mix and re-examining the impact on resource use and some of the more dominant emissions. Changing one parameter, however, can affect other input parameters that will also need to be adjusted for the inputs. If all the wood fuel was to be replaced with natural gas, the 363 kg of wood fuel would need to be replaced with 198 m^3 of natural gas based on the higher heating value (HHV) of each fuel. Some of the input wood needs to be reduced to affect a proper balance of input and output material flow. For this scenario 127 kg of green sawdust was removed from the input, which in turn reduced the amount of natural gas by 7.34 m^3 that was needed to dry this sawdust. Also the purchased bark hog fuel of 236 kg was not needed. Redoing the base-case SimaPro model to reflect the change in fuel mix from wood to all natural gas gives the life-cycle inventory output for the cradle-to-product gate values for resource use (in-ground raw material) and selected air emissions as shown in Table 1.13. Increasing the use of natural gas to displace all wood fuel use, decreases the carbon storage (CO_2 uptake by wood) effect by 33%, increases natural gas use by 143% and increased emissions of CO_2 fossil by 68%, methane by 86%, NMVOC by 109% and sulfur oxides (SO_x) by 100%. This results in a negative shift from emissions of CO_2 from a biogenic source that is considered global warming impact neutral to emissions from fossil fuel sources that do impact global warming. Decreases of emissions of benzene (61%), carbon monoxide (63%) and water use (~35%) also occur. Similar analyses of other major input parameters could be done to study their sensitivity and impact on the various output parameters. As the government legislate policies to reduce global warming through carbon cap and trade programs, emissions regulations, and the use of sustainable fuels, the use of wood as a substitute for fossil fuels and for fossil-fuel intensive products will become increasingly important. Furthermore, with increasing costs of fossil fuels and the possibility of a federal carbon tax on fossil fuel use, even more opportunities will develop for using wood as a fuel. These opportunities should be explored and developed further.

Table 1.13. LCI in terms of raw materials and air emissions for scenario of using natural gas to displace all wood fuel use in manufacture of MDF.

	Base case 82% wood-18% nat gas		Natural gas case 100% natural gas		Difference Gas-base
Raw Materials	**lb/MSF**	**kg/m^3**	**lb/MSF**	**kg/m^3**	**%**
Carbon dioxide in air	8,147	2,088	5,462	1,400	-33
Coal in ground	466	119	469	120	1
Natural gas in ground	480	123	1,167	299	143
Limestone in ground	80	21	27	7	-66
Crude oil in ground	192	49	188	48	-2
Uranium in ground	0	0	0	0	0
Water, cooling, unspecified natural origin	1,804	462	1,804	462	0
Water, lake	32	8	32	8	0
Water, process and cooling, unspec.natural origin	42	11	42	11	0
Water, process, unspecified natural origin	241	62	241	62	0
Water, process, well, in ground	540	138	457	117	-15
Water, river	87	22	87	22	0
Water, unspecified natural origin/m3	4,107	1,053	4,107	1,053	0
Water, well, in ground	1,860	477	2	0	-100
Wood fuel	1,530	392	108	28	-93
Emissions to air					
Acetaldehyde (HAP)	0.0023	0.0006	0.0023	0.0006	0
Acrolein (HAP)	0.000017	0.000004	0.000017	0.000004	1
Benzene	0.0084	0.0022	0.0033	0.0008	-61
Carbon dioxide, biogenic	3,201	820	228	59	-93
Carbon dioxide, fossil (GHG)	2,285	586	3,850	987	68
Carbon monoxide	26	7	9	2	-63
Formaldehyde (HAP)	0.7	0.2	0.6	0.2	0
HAPs	1.5	0.4	1.5	0.4	0
Mercury	0.000035	0.000009	0.000036	0.000009	2
Methane (GHG)	5.3	1.4	9.8	2.5	86
Methanol (HAP)	1.0	0.2	1.0	0.2	0
Nitrogen oxides	13	3	15	4	19
NMVOC, non-methane	5.8	1.5	12.1	3.1	109
Particulates	1.5	0.4	1.5	0.4	0
Particulates, < 10 um	3.2	0.8	3.0	0.8	-5
Phenol (HAP)	0.008	0.002	0.008	0.002	0
Sulfur oxides	24	6	48	12	100
VOC	3.6	0.9	3.6	0.9	0

1.9 Carbon balance for MDF Production

Carbon was tracked for the production of MDF. Approximately half the mass of wood consists of carbon, thus by tracking wood flow in and out of the manufacturing process a balance can be determined for the biogenic carbon flow. A check list was derived to balance the inputs of carbon with the outputs to determine if any carbon was missing and to also follow carbon in the life cycle of MDF manufacture. This analysis followed carbon from the inputs of wood materials through production of product 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 and plywood as 52.43% (Milota et al 2005, Wilson and Sakimoto 2005) which provided the input wood residue LCI data. Table 1.14 give the carbon content of wood materials from input to output. The input consists of wood shavings, sawdust, chips, ply trim, and purchased bark hog fuel, and the outputs of MDF, bark mulch, wood waste, and wood emissions to air, land, and water. The wood carbon content of 1.0 m^3 of MDF is 353 kg, which remains stored in the product in use or eventually in a landfill until it decays or is burned. The amount of carbon emissions to the atmosphere is 209 kg, mostly in the form of CO_2 which is recycled back into trees during their growing process, releasing oxygen back to the atmosphere. Only a small amount of carbon (2 kg) ends up in landfill which remains stored until it decays which can be decades and even centuries. The difference between the inputs and outputs is 4.6% with more wood flow out than in which can be attributed to higher than expected CO_2 emissions calculated for the combustion of wood fuel using the FAL database in SimaPro.

Table 1.14. Tracking of wood-based carbon inputs and outputs for MDF production.

			Carbon	Elemental carbon	
Inputs	**lb/MSF**	**kg/m^3**	**%**	**lb/MSF**	**kg/m^3**
Green chips	1,666	427	52.4	874	224
Green shavings	240	62	52.4	126	32
Dry shavings	489	125	52.4	256	66
Green sawdust	590	151	52.4	309	79
Plywood trim	109	28	52.4	57	15
Bark hog fuel purchased	919	236	52.4	482	124
Total				2,104	539
Outputs					
MDF (wood only)	2,576	660	52.4	1,350	346
Bark mulch sold	50	13	52.4	26	7
Wood boiler fuel sold	0.24	0.06	52.4	0.13	0.03
Sum of air emissions				816	209
Sum of water emissions	0.04	0.01	52.4	0.02	0.01
Sum of land emissions	16	4	52.4	8	2
Total				2,201	564
Outputs-inputs difference %				4.6	4.6

1.10 Study discussion

The data documented in this report on the manufacture of MDF forms a foundation for the scientific assessment of its environmental performance. The data can be used in a number of ways to shows its favorable performance in environmental issues such as sustainability, global warming, climate change, carbon storage, carbon trading and caps, carbon taxes, bio-fuel use, green purchasing, and green building. The data can be used as stated or in a life-cycle assessment to compare wood products to various competitive materials or assemblies of materials.

The Intergovernmental Panel on Climate Change (IPCC) conceptually recognized the potential of mitigating climate change by substitution for fossil fuel and fossil-fuel intensive products (IPCC 1991). The human-induced greenhouse effect could be reduced if wood was used to substitute for competitive materials saving on energy to produce these materials and on the consequent carbon emissions prevalent with these products. The carbon emissions from combustion of wood are considered global-warming-impact neutral because trees can absorb CO_2 from the atmosphere, storing the carbon as wood tissue and releasing the oxygen back to the environment. IPCC described three strategies associated with wood to reduce CO_2 in the atmosphere; two of the three included the use of wood products (IPCC 1996). They later stated that the substitution effect of wood products for fossil-fuel intensive products provide cumulative and permanent avoidance of fossil carbon emissions, while storage in trees provide limited, and possibly transient emissions avoidance. Simply put it is environmentally more effective to use trees for products that displace fossil-intensive products for reducing carbon emissions to the atmosphere than it is to store the carbon in trees (IPCC 2001 and Sathre 2007). These same strategies are addressed with the manufacture of MDF where wood is used as a significant portion of its energy need, displacing fossil fuel use, and as a product it can be used to displace fossil-intensive products such as plastic, steel, glass and cement.

Life-cycle inventory (LCI) data are invaluable when it comes to establishing the *greenness* of a product and its performance in comparison to competitive materials. The data forms the foundation for a scientific assessment with outputs in terms of a variety of environmental performance measures. It provides data that can be used to establish the performance of MDF for many green type standards, guidelines and policies. Such topics where the data can be used are sustainability, global warming, climate change, carbon storage, carbon trading and caps, carbon taxes, bio-fuel use, green purchasing, and green building. The data can be effective at establishing MDF performance in comparison to other materials by conducting life-cycle assessments with output measures in terms of impacts on human health, environment, and resource use.

Individual LCI data can be used as a benchmark for process or product improvements or for comparing performance to those of other materials. A life-cycle assessment (LCA) based on the LCI data can be used when comparing materials or assemblies comprised of various materials. The LCA output is given in terms of environmental performance indices of human health, environment, and resource impacts. Such a comparison was conducted by CORRIM in its assessment of residential structures that were built with various materials of wood, concrete, and steel (Perez-Garcia et al. 2005). In this assessment wood was shown to perform environmentally the best in most categories of comparison. MDF is not a structural building material; it is used for non-structural applications such as for cabinets, tables, countertops, furniture, and millwork. For an LCA approach to establish MDF's environmental performance it would therefore be effective to conduct an analysis based on comparison of various assemblies in terms of finished tables, desk, and cabinets comprised of their components. In this manner a desk comprised of MDF and other materials could be compared to a desk made of metal, glass, and other materials.

One approach to assessing the quality of the LCI data collected and analyzed is to compare it to existing data in the literature. This can be done by comparing the data in this report to data reported earlier by NCASI for emissions generated in the production of MDF (NCASI 1999). Another comparison can be made to LCI data reported by Rivela and others for MDF production in Spain (2 mills) and Chile (1 mill) (Rivela et al. 2007). NCASI did a study in the late 1990s assessing the emissions of various wood product manufacturing operations in terms of their sources within the mill. Table 1.15 gives a comparison of the NCASI values to those of this study for VOC, methanol and formaldehyde. The emissions differed in that methanol and total VOC were higher and the formaldehyde was lower for the NCASI data. In the NCASI report they pointed out that the greatest source of emissions within the mill was due to the blowline (tube dryer) where emissions occur due to the elevated temperatures of both the wood and resin. HAP emissions which include methanol and formaldehyde are expected to change for the MDF industry with the implementation in 2007/2008 of PCWP MACT regulations (USEPA 2004). With the implementation of this rule, those mills that cannot meet its regulations will be required to install emission control systems based on RTO, RCO, and BF technologies that use large quantities of natural gas and electricity to combust or "eat" HAP emissions.[3] As such, mill VOC and HAP emissions will decrease, however, emissions of SOx, NOx, CO_2 fossil, CO and those emissions associated with the generation of electricity off-site will significantly increase.

[3] To reduce VOC and HAP emissions, RTOs use large amounts of natural gas to combust the emissions, and large amounts of electricity to operate fans to transport the emissions; RCOs use a combination of a catalytic converter and the combustion of natural gas as well as electricity to operate the fans; and BFs use bio-organisms to convert emissions, and electricity to operate fans (no natural gas is needed, however electricity use can be as great or greater than to operate a RCO or RTO).

Table 1.15. Comparison of on-site emissions data with that collected by NCASI (1999).

	Wilson data		NCASI data[1]		NCASI-CORRIM Difference
Emission	**lb/MSF**	**kg/m^3**	**lb/MSF**	**kg/m^3**	**%**
Methanol	0.86	0.219	1.22	0.313	43
Formaldehyde	0.62	0.159	0.47	0.120	-24
Total VOC	3.28	0.841	5.68	1.455	73

[1] Sum of all source emissions averaged.

Table 1.16 gives a comparison of LCI data from this study to data for production of MDF produced in state-of-art mills in Spain and Chile (Rivela et al. 2007). These studies differ in their boundary system conditions, but still can be compared on the mill level in terms of inputs and outputs. The Rivela et al LCI study of MDF ignores the environmental impacts associated with the growing, harvesting, and residue processing of all wood inputs to the manufacturing process; they treat the wood as true waste with no burden other than transportation. The burden associated with the input wood residue becomes more significant as the percentage of dry wood residue increases. The reason for this is that energy is needed to dry the wood residue prior to its delivery to the MDF mill. In this Wilson LCI study of MDF the wood residue contributes 8% (1,683 MJ/m^3) to the total cradle-to-gate energy use (see Table 1.11) where only 17% of the material is dry coming into the mill. For the Rivela et al study, where about 50% of the material is dry going into the mill, the environmental burden of producing the residue would be significantly higher than the 8% contribution, somewhere in the range of 16-32%. As such, the wood residue in the Rivela et al study would be a significant contributor to the environmental burden and should not have been ignored. Despite this boundary condition difference, other major differences are that the MDF in the Rivela et al study is 24% less dense, the wood input is much drier, and the solids contents of input resin, additives and the moisture content of the wood fuel are not stated. These conditions of the studies explain much of the differences in the data and unfortunately provide several questions about the data. The values of the two data sets are similar for input materials (except resin), electricity and transportation, and but differ as expected for input resin and wood fuel where they are less for the Rivela et al data. The biggest difference is the input water which can be explained by the fact that the Rivela et al water input is only for employee's use and not processing. As for the Rivela et al output data their MDF product data has a very low density (566 kg/m^3) compared to the Wilson product density data (741 kg/m^3) for the US, they are very different products when it comes to MDF. Output data for the Rivela et al study have limited air emissions data, with particulate three times greater and formaldehyde four times less, other wood composite processing related emissions are not given. As for the lesser formaldehyde data, the Rivela et al study does not describe emissions any control equipment, whereas in the Wilson study only one of the mills had RTO/RCO equipment to mitigate formaldehyde emissions at the time of the survey.

Table 1.16. Comparison of MDF on-site inputs and outputs to Rivela et al (2007) averaged data for two Spanish mills and one Chilean mill.

INPUTS	Unit	Wilson[1] Unit/m^3	Rivela et al[2] Unit/m^3
Materials			
Wood residue	kg	673	699
Urea-formaldehyde (UF) resin	kg	83	44
Ammonium-sulfate catalyst	kg		0.24
Wax	kg	5.21	3.22
Urea scavenger	kg	1.28	1.43
Electricity	MJ	1,494	1,271
Fuels			
Natural gas	m^3	43.2	
Diesel	l	0.43	
LPG	l	0.76	
Gasoline and kerosene	l	0.13	
Distillate fuel oil	l	0.27	
Wood fuel	kg	359	219
Water Use	l	1,387	57
Transportation (trailer)	tkm	289	300
OUTPUTS			
Product	**SI Unit**	**SI Unit/m^3**	**SI Unit/m^3**
Medium density fiberboard (MDF)	kg	741	566
Bark mulch sold	kg	13	
Air Emissions			
Total VOC	kg	0.84	
Particulate	kg	0.36	1.76
Particulate (PM10)	kg	0.29	
Formaldehyde	kg	0.16	0.045
Methanol	kg	0.22	
Waste	kg	4.1	1.7

[1] All wood wieghts whether furnish, MDF, bark or fuel are oven dry; chemical wieghts are 100% solids.

[2] Oven dry weights given for wood furnish and MDF based on moisture condition that "% water condition" is on a wet-basis weight; solids content of chemical and wood fuel inputs not stated; water use auxiliary for employee's use.

1.11 Conclusion

A cradle-to-product gate life-cycle inventory (LCI) study was conducted of manufacturing 1.0 MSF ¾-inch basis—the industry functional unit—and 1.0 m^3 —the LCI functional unit—of medium density fiberboard (MDF) in the U.S. The study covered data analyses from the resources in the ground through MDF manufacturing based upon prior CORRIM studies for forest resources, harvesting, transportation, input wood resources consisting of wood shavings, sawdust and chips from the manufacture of softwood lumber and plywood, resin, and survey-collected data of four MDF manufacturing mills for the production year 2004. The mills represented 27.6% of total U.S. production with the average mill annually producing 208,305 m^3 of MDF at an average dry density of 741 kg/m^3. The MDF panel is comprised of 89.1 % wood, 10.1% urea-formaldehyde resin, 0.6% wax, and 0.2% urea scavenger—all on an oven dry or 100% solids basis weight.

The quality of the LCI data collected for the manufacture of MDF 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 the input wood to the process. Any outliers were resolved by re-contacting the manufacturers that participated in the survey. The mass balance of input and output material had only a 0.3% difference which is within the specified 5% of the CORRIM protocol. The energy to dry the wood in the process was 2,109 Btu/lb (4.91 MJ/kg) of water removed based on the lower heating value of the fuels which is close to the expected 2,000 Btu/lb (4.65 MJ/kg) value based upon experience with drying other wood products.

Assigning of environmental burden in the production of MDF was totally to the product since only a small portion of the mill production resulted in other products. Of the output, 741 kg was for MDF, 12.9 kg was for bark mulch that was sold and according to CORRIM protocol was not assigned a burden, and 0.06 kg was sold for fuel and because it is relatively a small quantity in comparison to the product, it too was not assigned a burden.

The embodied energy to produce MDF consists of fuels and electricity used on-site and the fuels used off-site to generate and deliver fuels and electricity to the mill, and those fuels used to manufacture input materials such as wood, resin, wax and scavenger. The on-site energy which includes all fuels and electricity was 10,723 MJ/m^3. Of the fuel use on-site to provide process heat, wood fuel provided 82%, and in terms of the total on-site energy, the wood fuel provided 70%. This is important since wood is a sustainable, renewable fuel that is substituting for fossil fuel, a non-renewable fuel. The other 18% of the process heat was provided by natural gas. The total embodied energy of manufacturing MDF from resource in the ground through product manufacture, also referred to as cradle-to-product gate, was 20,707 MJ/m^3 which as expected is significantly higher than the on-site use. The total energy covers both the on-site and off-site energy use. A breakdown of the total energy in terms of its contribution can be stated in terms of the fuel type or in terms of its major components. In terms of fuels the major contributors are wood at 39.6%, natural gas at 32.3%, coal at 15.1%, oil at 10.8%, plus a number of insignificant fuel contributors. In terms of the major component contributors, wood fuel is 37.3%, electricity 21.8%, urea-formaldehyde resin 18.9% and wood residue (consisting of sawdust, sander dust, shavings, and chips) at 8.1% and a large number of other minor contributors that total 13.9%. In both cases, wood for fuel as an energy source plays a significant and favorable environmental role; its increased use should be explored.

The source of fuels to generate electricity delivered to the mills for processing plays an important role in any life-cycle inventory assessment. A U.S. average for generating electricity by fuel source was selected for this study consisting of 49.8% coal, 19.9% nuclear, 17.9% natural gas, 6.8% hydroelectric, 3.0% oil, and smaller percentages of other sources.

Of the on-site emissions for manufacturing MDF, wood fuel generated 762 kg/m^3 of CO_2, some of the CO that totaled 5 kg, and all of the VOC, particulate and HAPs. Combustion of natural gas, and the use of a small amount of fuels to operate equipment such as fork lift trucks, generated 83.4 kg/m^3 of CO_2 and some of the carbon monoxide, methane, and most of the NOx and SOx with a small amount due to wood fuel combustion. Emissions of CO_2 biogenic due to the combustion of wood, has a neutral impact on global warming according to the EPA (USEPA 2003); whereas CO_2 due to combustion of fossil fuels such as natural gas contribute significantly to global warming. Other on-site emissions consisted of VOC at 0.84 kg, total particulates at 0.65 kg, formaldehyde at 0.16 kg and methanol at 0.22 kg. Only a small amount of waste is generated on-site, with 1.94 kg of boiler fly ash and 2.21 kg of wood waste going to the landfill. The total emissions, considering both on-site and the off-site to generate fuels, electricity, resin, and other inputs, resulted in 820 kg of CO_2 biogenic, and 586 kg of CO_2 fossil—an increase over on-site emissions of 8% for CO_2 biogenic and 600% for CO_2 fossil. Of the total emissions, the on-site contributes the majority of the CO_2 biogenic (93%) and only 14% of the CO_2 fossil and for other emissions it contributes 77% for CO, 26% for formaldehyde, 27% for methanol, 12% for nitrogen oxides, 38% for total particulates and 90% for VOC.

It is significant that during the cradle-to-gate process of producing MDF that the growing of trees results in an uptake of CO_2, storing carbon in wood substance and releasing oxygen back to the atmosphere. About half the mass of wood and bark is carbon; to determine the equivalent of carbon dioxide that was removed from the air to form this carbon in wood and bark, multiply their carbon content in kg by 3.67 kg CO_2/kg oven dry wood or bark. To produce 1.0 m^3 of MDF from seed to product the CO_2 removed from the atmosphere, listed as "carbon dioxide in air" which includes equivalents for carbon store in MDF and wood fuel, is 2,088 kg which can be used to offset the CO_2 emissions of 820 kg due to combustion of biogenic fuel and 586 kg due to combustion of fossil fuel. This leaves sufficient remaining carbon store to offset other greenhouse gas emissions due to the delivery, use and disposal of MDF, and even offset some CO_2 in the atmosphere; in turn reducing their impact upon global warming. This carbon storage remains in the MDF for the life of its useful service and even longer if recycled or placed in a modern landfill where much of it can last for over a 100 years.

A sensitivity study was conducted to examine the impact of using more fossil fuel in the MDF manufacturing process. For the survey-collected data, 82% of the on-site process heat was provided by wood fuel and 18% by natural gas. To study the effect of fuel type on the environmental impact the wood fuel was decreased to 0% and the natural gas use increased to 100%. This resulted in adjusting a number of the input components such as wood fuel and input wood needed for the board to account for these changes. For a cradle-to-product gate study of the 100% natural gas use scenario in comparison to the survey data, the natural gas in the ground resource increased by 143% and water use decreased substantially. As expected the emissions increased for CO_2 fossil (68%), methane (86%) and NOx (19%)—all contributors to global warming, and increased for non-methane VOC (109%) and SO_x (100%). While emission decreases occurred for CO_2 biogenic (-93%), CO (-63%), and benzene (-61%). If the goal is to reduce global warming then substituting natural gas for wood fuel to generate process heat is a bad decision for the environment and resource depletion.

To benefit from the availability of the LCI database for MDF the following studies are recommended: 1) extract pertinent data that documents the favorable environmental performance of MDF, 2) develop life-cycle inventory data from the MDF output mill gate through its incorporation into secondary products such as office and residential furniture, through its service life and eventual disposal or recycle, 3) conduct a life-cycle assessment of MDF in comparison to selected alternative materials and products, and 4) extend the study on the impact of fuel type and amount of use on the environment, human health, and resource depletion.

2.0 References

ANSI. 2002. American National Standard. ANSI A208.2-2002. Medium Density Fiberboard (MDF) for Interior Applications. Composite Panel Association, Gaithersburg, MD. pp 11.

Composite Panel Association (CPA). 2005. 2004 North American Shipments Report – Particleboard, Medium Density Fiberboard, and Hardboard. CPA, 18922 Premiere Court, Gaithersburg, MD 20879.

CORRIM. 2001. Research Guidelines for Life Cycle Inventories. Consortium for Research on Renewable Industrial Materials. (CORRIM, Inc.) Seattle, WA. 2 Apr. 47 pp.

Ecoinvent. 2004. Ecoinvent Database and Methodology. Data version 1.1. http://www.ecoinvent.org/fileadmin/documents/en/01_OverviewAndMethodology.pdf June. (15 Jan 08)

Ecoinvent. 2007. Ecoinvent Database and Methodology. Data version 2.0. http://www.ecoinvent.org/fileadmin/documents/en/01_OverviewAndMethodology.pdf Dec. (15 May 08)

Energy Information Administration (EIA). 2007. Net Generation by Energy Source by Type of Producer, 1995 through 2006 http://www.eia.doe.gov/cneaf/electricity/epa/epat1p1.html. (27 Nov 07)

Franklin Associates LTD (FAL). 2004. The Franklin Associates Life Cycle Inventory Database. SimaPro7 Life-Cycle Assessment Software Package version 7.1 http://www.pre.nl/download/manuals/DatabaseManualFranklinUS98.pdf June. (15 Jan 08)

Intergovernmental Panel on Climate Change (IPCC). 1991. Climate Change: the IPCC Response Strategies. Island Press, Washington D.C.

____. 1996. Climate Change 1995- Impacts, Adaptations and Mitigation of climate Change: Scientific-Technical Analyses. Cambridge University Press, Camabridge, UK.

____. 2001a. Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report. Cambridge Unviersity Press, Cambridge, UK.

____. 2001b Climate Change 2001: The Mitigation. Contribution of Working Group III to the Third Assessment Report. Cambridge Unviersity Press, Cambridge, UK.

International Organization for Standardization (ISO). 2006a. Environmental management-life cycle assessment-principles and framework. ISO 14040. First Editon 2006-06-31. Geneva, Switzerland. 32 pp.

____. 2006b. Environmental management—life cycle assessment—Requirements and guidelines. ISO 14044. First Edition 2006-07-01. Geneva, Switzerland. 46 pp.

Johnson, L.R., B. Lippke, J.D. Marshall, and J. Comnick. 2005. Life-cycle impacts of forest resource activities in the Pacific Northwest and Southeast United States. Wood Fiber Sci. 37 CORRIM Special Issue:pp. 30-46.

Milota, M. R., C. D. West, and I. D. Hartley. 2005. Gate-to-gate life inventory of softwood lumber production. Wood Fiber Sci. 37 CORRIM Special Issue:pp. 47-57

National Renewable Energy Laboratory (NREL). 2007. Life-cycle inventory database project. http://www.nrel.gov/lci/. (27 Feb 2007).

National Council for Air and Stream Improvement, Inc. (NCASI). 1999. Volatile Organic Compound Emissions from Wood Products Manufacturing Facilities. Part III ─ Medium Density Fiberboard. Technical Bulletin No. 770. Research Triangle Park, N.C. January.

Perez-Garcia, J., B. Lippke, D. Briggs, J. B. Wilson, J. Bowyer, and J. Meil. 2005. The Environmental Performance of Renewable Building Materials in the Context of Residential Construction. Wood and Fiber Sci. 37 CORRIM Special Issue:pp. 3-17.

PRé Consultants. 2007. SimaPro7 Life-cycle assessment software package, Version 7.10. Plotterweg 12, 3821 BB Amersfoort, The Netherlands. http://www.pre.nl/simapro/manuals/default.htm. (27 Feb 07).

Rivela, B, M. Moreira and G. Feijoo 2007. Life Cycle Inventory of Medium Density Fibreboard. Int. J. LCA. 12(3): 143-150.

Sathre, R. 2007. Life-Cycle Energy and Carbon Implications of Wood-based Products and Construction. Mid Sweden University. Ostersund, Sweden. pp. 102 plus publication papers.

United States Department of Energy (USDOE). 2006. Net Generation by Energy Source by Type of Producer. http://www.eia.doe.gov/cneaf/electricity/epa/generation_state.xls (15 January 2007)

U.S. Census Bureau. 2007. 2002 NAICS Definitions. http://www.census.gov/epcd/naics02/def/ND321219.HTM. (27 Nov 07)

U.S. Environmental Protection Agency (USEPA). 2003. Wood waste combustion in boilers. 20 pp. *In* AP42 Fifth Edition Volume I Chapter 1: External combustion sources. http://www.epa.gov/tnn/chief/ap42/ch01/index.html. (18 Jan 08)

____. 2004. National Emission Standards for Hazardous Air Pollutants: Plywood and Composite Wood Products; Effluent Limitations Guidelines and Standards for the Timber Products Point Source Category; List of Hazardous Air Pollutants, Lesser Quantity Designations, Source Category List. http://www.epa.gov/EPA-WATER/2004/July/Day-30/w6298a.htm. (10 Dec 07)

____. 2007. Source Classification Codes. http://www.epa.gov/ttn/chief/codes/scc_feb2004.xls. (27 Nov 07)

Wilson, J.B., and E.T. Sakimoto. 2005. Gate-to-gate life-cycle inventory of softwood plywood production. Wood Fiber Sci. 37 CORRIM Special Issue:pp. 58-73

Wilson, J. B. 2009. Resins: A life-cycle inventory of resins used in the wood composites industry. Consortium for Research on Renewable Industrial Materials. (CORRIM, Inc.) Seattle, WA. pp. (In Progress)

Appendix 1: Medium Density fiberboard (MDF) survey form

CORRIM SURVEY

The Consortium for Research on Renewable Industrial Materials (CORRIM) 1-15-2005

The information from this survey will be used in a project by CORRIM, a consortia comprised of universities, industry, and government groups. CORRIM is conducting a life-cycle assessment that will describe environmental influences of wood products. CORRIM's objective is to acquire a database and produce life-cycle models of environmental performance for all wood products. We recently completed the database for structural wood products and are now doing other products. The database will be the basis for the scientific evaluation of feasible alternatives affecting the environmental releases and energy requirements of wood products through their life cycles. It is hoped that the output of the study will be used to competitively position wood in the marketplace over other types of materials.

This CORRIM survey is designed specifically for MDF mills. Questions will be concentrated on annual production, electricity production and usage, fuel use, material flows, and environmental emissions. We realize that you may not have all the information requested, especially when it comes to specific equipment and processing groups. The data you are able to provide will be appreciated. We intend to maintain the confidentiality of data and companies participating in this survey. Please contact me if you have any questions.

Company: ______________________________

Facility Site (city, state): ______________________________

Should we have a follow-up question about the data, please provide the name and the following information for the contact in your company.

Name: ______________________ Title: ______________________

Telephone: ______________________ E-mail: ______________________

If you have questions about the survey, please contact me. **Either mail or fax completed survey to:**

Jim Wilson
Professor
Department of Wood Science and Engineering
234 Richardson Hall
Oregon State University
Corvallis, OR 97331-5751
541-737-4227 phone
jim.wilson@oregonstate.edu

Annual Production (Please provide units of measurement if different than stated.)

		State basis used	TOTAL ANNUAL PRODUCTION
1.	MDF produced in 2004 (preferred) or 2003; circle year for data	MSF 3/4-inch basis	______________
	give production year if different		______________
2.	Estimated average density of panels	lb/ft^3	______________
3.	Number of employees		______________
4.	Number of production lines		______________
5.	Year of installation of each line:		
	Line 1		______________
	Line 2		______________
6.	Other materials sold (i.e., sander dust)		______________
	a.	lb. or tons (dry weight)	______________
	b.	lb. or tons (dry weight)	______________
	c.	lb. or tons (dry weight)	______________

Characteristics of Production Line(s)—we are required in our protocol to describe the manufacturing process and characterize the technology, thus the questions. If the raw material input to your plant is residue, after 1. Roundwood write "none" under description.

Line No. 1

	Unit process center	**Description**
1.	Roundwood debarking and reduction (Brand and type)	
2.	Refiners (Brand and type i.e., Pallmann flaker, pressurized disc refiner, hammermill, etc.)	
3.	Screens (Brand and type)	
4.	Dryers (Brand and type, i.e., flash tube, direct fired, sander dust or natural gas, recycle exhaust)	
5.	Blenders (Brand and type) and where resin and wax are injected to line	
6.	Formers (Brand and type)	
7.	Hot Press (Brand and type--platen or continuous, no. openings, platen size, steam or oil heat, RF assist, etc.)	
8.	Panel cooler (Brand and type)	
9.	Trim saws (Brand and type)	
10.	Sanders (Brand and type)	
11.	Other	

Line No. 2 (skip this question if you only have one production line)

	Unit process center	Description
1.	Roundwood debarking and reduction (Brand and type)	
2.	Refiners (Brand and type i.e., Pallmann flaker, pressurized disc refiner, hammermill, etc.?)	
3.	Screens (Brand and type)	
4.	Dryers (Brand and type, i.e., flash tube, direct fired, sanderdust or natural gas, recycle exhaust?)	
5.	Blenders (Brand and type)	
6.	Formers (Brand and type)	
7.	Hot Press (Brand and type--platen or continuous, number of openings, platen size, steam or oil heat, RF assist, etc.?)	
8.	Panel cooler (Brand and type)	
9.	Trim saws (Brand and type)	
10.	Sanders (Brand and type)	
11.	Other	

Annual Wood Use for Mill (Please provide units of measurement if different than stated.)

	Wood type (logs, shavings green, shavings dry, ply trim, sawdust, etc.)	MC of wood as delivered (% oven dry wood basis)	Annual Use Weight (tons or lbs oven dry, or volume; give units used)
1.			
2.			
3.			
4.			
5.			
6.			
7.			
8.			
	Total wood use		

Species Mix of wood residue used by plant

	Wood Species (either hardwood or softwood; or actual species if known)	% of Total mix
1.	Softwoods	
2.	hardwoods	
3.		
4.		
5.		
6.		
	Total	100%

Annual Energy Consumption (Total use for boilers, oil heaters, forklifts, etc. Please provide units of measurement if different.)

1.	Purchased electricity	kWh	______
2.	Purchased steam	lbs. (at temperature °F?)	______
	If you know fuel source used to generate steam, please state type, i.e. natural gas, hog fuel		______
3.	Coal	Tons (oven dry)	______
4.	Hog fuel *Self-generated*	Tons (oven dry)	______
	Purchased	Tons (oven dry)	______
	Wood waste	Tons (oven dry)	______
	Sander dust	Tons (oven dry)	______
	Residual fuel oil	42 Gal. Bbls.	______
	Distillate fuel oil	42 Gal. Bbls.	______
	Liquid propane gas	Gallons	______
	Natural gas	$ft.^3$	______
	Gasoline and kerosene	Gallons	______
	Diesel	Gallons	
	Other (Specify)		
	Less energy sold or transferred		
	a. Electricity	kWh	______
	b. Steam	lbs. (at temperature °F?)	______
	c. Hog fuel	Tons (oven dry)	______
	d. Wood waste	Tons (oven dry)	______

Note: please list fuel (i.e., propane, diesel, etc.) consumption in appropriate category above for use of fork lifts in mill.

Characteristics of heat sources

1. Do you have a boiler, fuel cell, or oil heater? Check appropriate boxes.
   - ☐ Boiler
   - ☐ Fuel cell
   - ☐ Oil heater
   - ☐ Other
2. If you have a boiler, what is its heat source? Check appropriate box.
   - ☐ Hogged fuel
   - ☐ Oil
   - ☐ Natural gas
   - ☐ Other
3. If you have a fuel cell, what is its heat source? Check appropriate boxes.
   - ☐ Hogged fuel
   - ☐ Oil
   - ☐ Natural gas
   - ☐ Other
4. If you have a oil heater, what is its heat source? Check appropriate box.
   - ☐ Hogged fuel
   - ☐ Oil
   - ☐ Natural gas
   - ☐ Other

Other Related Information on an annual basis

1. For dryer(s), check box for the heat source type and state the annual fuel consumption if known:

☐ Steam	lbs.	______
☐ Natural gas direct-fired	$ft.^3$	______
☐ Sander dust or other wood fuel direct-fired	Tons (oven dry weight)	______
☐ Other (please specify)	______	______

2. For dryer(s) specify the following:

☐ Type of dryer(s) (i.e. blow tube, etc.)	______
☐ How is dryer(s) heated (direct fired, heat exchanger, etc.)	______
☐ Do you recycle dryer exhaust, if so to where	______

3. For dryer(s):

☐ Green furnish dried and approximate percentage of total		
Average moisture content into dryer	% oven dry basis	______
Average moisture content out of dryer	% oven dry basis	______
Percentage of total wood dried	%	______
☐ Dry furnish dried and approximate percentage of total		______
Average moisture content into dryer	% oven dry basis	______
Average moisture content out of dryer	% oven dry basis	______
Percentage of total wood dried	%	______

4. Formulation and usage of resin, catalyst, and other components.		
Component type	% solids by weight	Total annual use (lbs.) on a solids or wet basis–please state basis
Urea formaldehyde		
Catalyst		
Wax		
Water		
Other resins (i.e., PMDI, MUF, PF) please state type:		
Other (please specify)		

5. Annual water use (check source(s) and give amount):

☐ Municipal water source Gallons ____________________

☐ Well water source Gallons ____________________

☐ Recycled water Gallons ____________________

6. Transportation method and average distance to deliver wood furnish (check method(s)):

Wood furnish (logs, residue, etc.) delivery method	Average haul one-way (miles)	% of Total Shipping
☐ Truck	________	________
☐ Rail	________	________
☐ Other	________	________
		Total= 100%

7. Transportation method used to deliver resin

	Average haul one-way (miles)	% of Total Shipping
☐ Truck		
☐ Rail		
☐ Other		
Total		100

8. Transportation method used to ship MDF panels

	Average haul one-way (miles)	% of Total Shipping
☐ Truck		
☐ Rail		
☐ Other		
		100

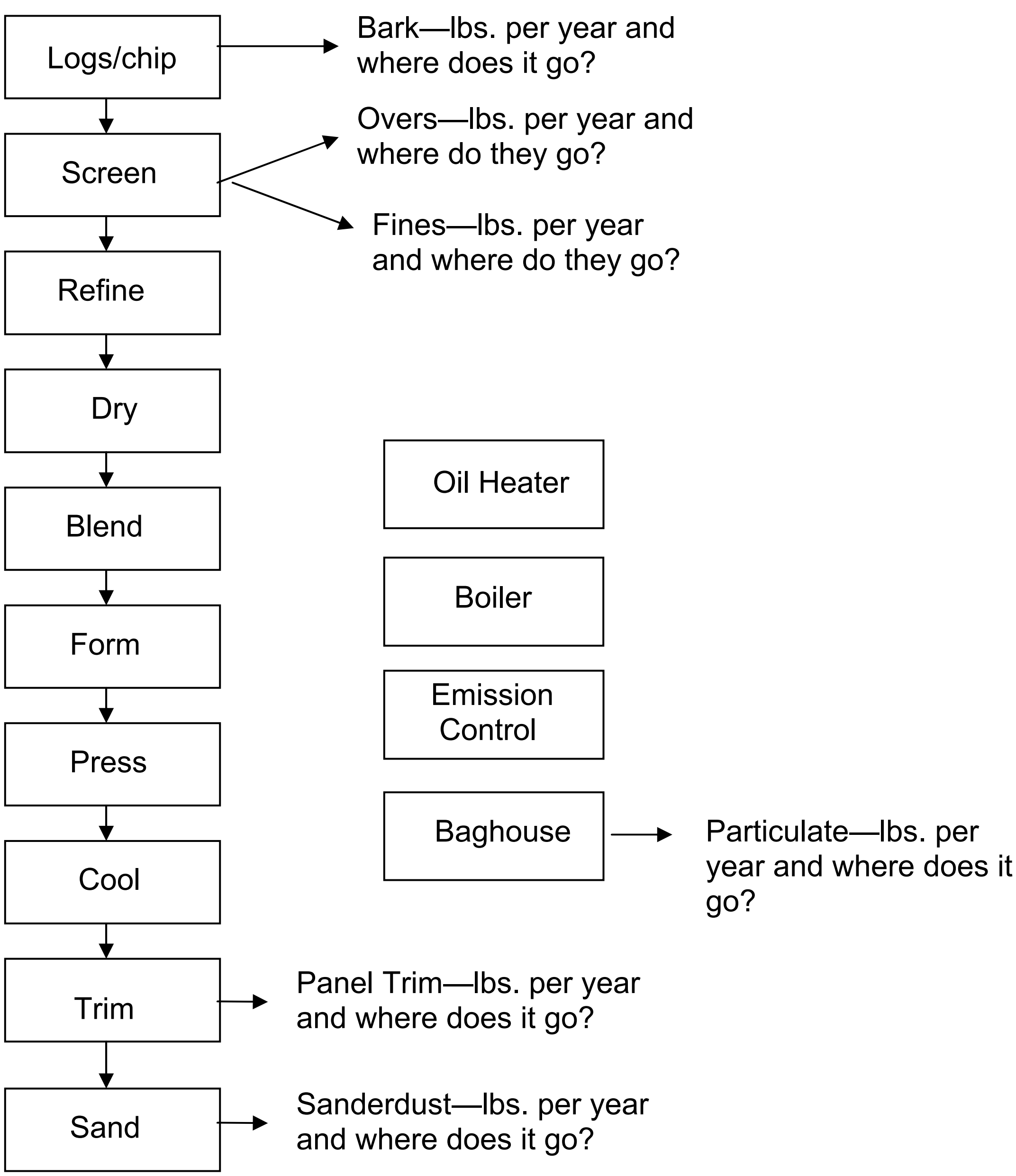
Annual Energy Use by Unit Process *–most mills won't have specifics, however, if you can provide the approximate use of energy in percentage of total mill use, this will be extremely helpful to us.*

Breakdown of Natural Gas Use	Percent (%) or Annual ft3 use
Dyers (if direct-fired)	
Boiler	
Oil Heater	
Emissions Control Devices	
Other	
Total	100% or __________ ft3

Breakdown of Electricity Use	Percent (%) or Annual kWh use
Debarking and log reduction	
Refiners	
Dryers	
Blenders	
Formers	
Press(es)	
Cooler	
Trim saws	
Sander(s)	
Boiler(s)	
Emissions control device(s)	
Other	
Total	100% or __________ kWh

Process and Material Flows

To enable us to model the flow through your operation we would like to know the process order and any by-products generated by the process and where they go. For the order, if the process flow depicted below isn't correct, i.e., your input is residue and not logs, draw a line through the box, or if the order isn't correct, i.e., the blender consists of putting the resin directly into the blow line, draw an arrow from the blender to where it is in your process. For the by-product give the lbs per year and where they go, if it goes back into the process, draw a line to where it goes. If there are other by-products, please write them in and provide information. For emissions, draw a line from the process to emission control device. If a process isn't shown, please add it. Please comment on any parts of you operation that you feel we should be aware of.



Annual Material Flow

This is a general material flow survey for medium density fiberboard mills. This survey is designed to trace all wood coming into the plant and out. You have already provided the input material and the output panel production, what we now need to track is by-products through the operation and where they go.

Unit Process	**Material type**	**Amount of material (lbs or tons oven dry?)**	**Where does it go? (back into a specific unit process, boiler, sold, etc.?)**
Debark logs	Bark		
Screen	Screening fines		
	Screening overs		
Saw & trim	Saw trim		
Sanding	Sander dust		
Bag house	Bag house dust		
Cyclone	Cyclone dust		
Other?			

MDF dryers. Please provide units of measurement in terms of annual use.

	Dryer No. 1	Dryer No. 2	Dryer No. 3	Dryer No. 4
Annual Dryer Throughput: **(dry weight basis, lbs or tons)**				
Dryer fuel consumption:				
Wood waste (i.e., sander dust; lbs or tons)				
Natural gas (ft^3 or Dtherm)				
Propane (gal.)				
Other? Please state what				
Heating method; check method that applies:				
Direct-fired				
Indirect-fired **(heat exchanger)**				
Dryer type; check type that applies:				
Blow tube				
Other (please name)				

Emission Control Devices and Environmental Emissions

The following is a chart of emission control devices and on the following page is a listing of chemical compounds that are observed and/or permitted. Please fill in all information related to the control devices. Then list all compounds that are collected and known for the mill from all control device sources. If you recently applied for an air permit, use those numbers. Fill in all that apply and for which you have data. If you have more than five devices, please make a copy of this page and the next, change numbers from 1 to 6, i.e. ECD 1 to ECD 6, complete form and attach.

Emission Control Device (ECD) - Electricity, Fuel Usage and Emission Output

	ECD 1	**ECD 2**	**ECD 3**	**ECD 4**	**ECD 5**
Equipment type controlled (boiler, dryer, press, oil heater, etc.?)					
Type of device (RTO, RCO, Scrubber, WESP, cyclone, baghouse, etc.?)					
Manufacturer and year installed					
ECD exhaust temperature (^{o}F) and flow rate (acfm)					
Electricity use in % of total mill use or kWh, please state units					
Natural gas use in % of total mill use or ft.^{3} or Dtherm, please state units					

Annual Emissions to Air (provide data for same device identified on prior page; please provide unit of measurement for each.)					
Organic Compound	**ECD 1**	**ECD 2**	**ECD 3**	**ECD 4**	**ECD 5**
Equipment type controlled (boiler, dryer, press, etc.)					
Units	**Tons/year**	**Tons/year**	**Tons/year**	**Tons/year**	**Tons/year**
CO_2 (you probably don't have this number but provide if you do)					
CO					
NO_X					
SO_X					
Total VOC					
Particulates					
PM10					
Lead					
Acrolien*					
Acetaldehyde*					
Propionaldehyde*					
Formaldehyde*					
Methanol*					
Phenol*					
Water Vapor					
*** HAPS; provide total HAPS if you have data, also provide whatever individual HAPS that you record or measure**					
Other (Please Specify					

Solid Emissions to Land From All Known Sources (please provide units of measurement)		
Emission	**Amount (i.e., tons, lbs.—give units)**	**Method of disposal or end use (i.e., land fill)**
Wood waste		
Boiler ash and fly ash		
Recovered particulates from pollution abatement equipment		
Other (please specify)		

Emissions to Water From All Known Sources (please provide units of measurement)		
Emission	**Quantity (i.e., tons, lbs.)**	**Method of disposal or end use (i.e., sewer)**
Suspended solids		
Dissolved solids		
BOD		
COD		
Chlorides		
Oil and grease		
Other (please specify)		
pH of discharged water		

Appendix 2: Contributors to emission outputs for LCI

			Input resources					Boiler fuels				Equipment fuels		
Substance	**Total**	**MDF proc.**	**Furnish**	**UF resin**	**Wax**	**Urea scav.**	**Transpor**	**Nat. gas**	**Wood**	**DFO**	**Electricity**	**Nat. gas**	**Gas**	**Diesel**
Calcite in ground	100	0	0	99	0	1	0	0	0	0	0	0	0	0
Clay in ground	100	0	0	99	0	1	0	0	0	0	0	0	0	0
Coal in ground	100	0	5	7	0	0	0	0	0	0	88	0	0	0
Crude oil in ground	100	0	0	1	99	0	0	0	0	0	0	0	0	0
Crude oil, 42 MJ per kg, in ground	100	0	22	43	1	1	15	1	4	1	12	0	0	1
Electricity from other gases	100	0	0	7	0	0	0	0	0	0	93	0	0	0
Electricity from other renewables	100	0	0	7	0	0	0	0	0	0	93	0	0	0
Energy, from hydro power	100	0	48	4	0	0	0	0	0	0	48	0	0	0
Gravel in ground	100	0	0	99	0	1	0	0	0	0	0	0	0	0
Iron ore in ground	100	0	100	0	0	0	0	0	0	0	0	0	0	0
Limestone in ground	100	0	2	2	0	0	0	0	67	0	29	0	0	0
Natural gas in ground	100	0	6	42	0	0	0	33	0	0	18	0	0	0
Nickel in ground	100	0	0	99	0	1	0	0	0	0	0	0	0	0
Sodium chloride in ground	100	0	0	100	0	0	0	0	0	0	0	0	0	0
Uranium in ground	100	0	5	7	0	0	0	0	1	0	86	0	0	0
Water, cooling, unspecified natural origin	100	0	0	75	25	0	0	0	0	0	0	0	0	0
Water, lake	100	0	0	100	0	0	0	0	0	0	0	0	0	0
Water, process and cooling, unspecified natural origir	100	0	100	0	0	0	0	0	0	0	0	0	0	0
Water, process, unspecified natural origin	100	0	0	91	7	2	0	0	0	0	0	0	0	0
Water, process, well, in ground	100	0	92	8	0	0	0	0	0	0	0	0	0	0
Water, river	100	0	0	100	0	0	0	0	0	0	0	0	0	0
Water, unspecified natural origin	100	89	0	8	3	0	0	0	0	0	0	0	0	0
Water, well, in ground	100	95	1	4	0	0	0	0	0	0	0	0	0	0
Wood and wood waste	100	0	100	0	0	0	0	0	0	0	0	0	0	0
Wood and wood waste	100	0	0	0	0	0	0	0	100	0	0	0	0	0
Wood direct fired fuel	100	0	100	0	0	0	0	0	0	0	0	0	0	0
Wood hog fuel self-generated MDF	100	0	0	0	0	0	0	0	100	0	0	0	0	0
Wood MDF sander dust for fuel	100	0	0	0	0	0	0	0	100	0	0	0	0	0
Energy														
Energy from hydro power	100	0	48	4	0	0	0	0	0	0	48	0	0	0
Electricity from other gases	100	0	0	7	0	0	0	0	0	0	93	0	0	0
Electricity from other renewables	100	0	0	7	0	0	0	0	0	0	93	0	0	0

			Input resources					Boiler fuels				Equipment fuels		
Emissions to air	**Total**	**MDF proc.**	**Furnish**	**UF resin**	**Wax**	**Urea scav.**	**Transpor**	**Nat. gas**	**Wood**	**DFO**	**Electricity**	**Nat. gas**	**Gas**	**Diesel**
Acetaldehyde	100	0	83	16	0	0	0	0	0	0	0	0	0	0
Acetic acid	100	0	0	99	0	1	0	0	0	0	0	0	0	0
Acetone	100	0	62	38	0	1	0	0	0	0	0	0	0	0
Acrolein	100	0	7	7	0	0	0	0	0	0	85	0	0	0
Aldehydes, unspecified	100	0	26	22	0	0	42	2	0	0	7	0	0	0
alpha-pinene	100	0	100	0	0	0	0	0	0	0	0	0	0	0
Aluminum	100	0	0	99	0	1	0	0	0	0	0	0	0	0
Ammonia	100	0	0	98	0	1	0	0	0	0	1	0	0	0
Arsenic	100	0	5	18	0	0	0	0	57	0	19	0	0	0
Barium	100	0	7	0	0	0	0	0	93	0	0	0	0	0
Benzene	100	0	5	34	0	0	0	0	61	0	0	0	0	0
Beta-pinene	100	0	100	0	0	0	0	0	0	0	0	0	0	0
Butane	100	0	0	99	0	1	0	0	0	0	0	0	0	0
Cadmium	100	0	2	76	0	1	0	1	0	0	20	0	0	0
Calcium	100	0	0	98	0	1	0	0	0	0	0	0	0	0
Carbon dioxide, biogenic	100	0	7	0	0	0	0	0	93	0	0	0	0	0
Carbon dioxide, fossil	100	0	9	20	1	0	4	16	0	0	50	0	0	0
Carbon disulfide	100	0	0	99	0	1	0	0	0	0	0	0	0	0
Carbon monoxide	100	0	11	4	0	0	3	3	76	0	2	0	1	0
Chlorine	100	0	7	0	0	0	0	0	92	0	0	0	0	0
Chromium	100	0	5	26	0	0	0	0	37	0	30	0	0	0
Cobalt	100	0	1	85	0	1	0	0	0	0	12	0	0	0
Copper	100	0	0	99	0	1	0	0	0	0	0	0	0	0
Dinitrogen monoxide	100	0	3	38	0	1	0	0	0	0	58	0	0	0
Ethanol	100	0	0	99	0	1	0	0	0	0	0	0	0	0
Formaldehyde	100	95	4	1	0	0	0	0	0	0	0	0	0	0
HAPS	100	100	0	0	0	0	0	0	0	0	0	0	0	0
Hydrocarbons, aliphatic, alkanes, unspecified	100	0	0	99	0	1	0	0	0	0	0	0	0	0
Hydrocarbons, aliphatic, unsaturated	100	0	0	99	0	1	0	0	0	0	0	0	0	0
Hydrocarbons, aromatic	100	0	0	99	0	1	0	0	0	0	0	0	0	0
Hydrocarbons, unspecified	100	0	100	0	0	0	0	0	0	0	0	0	0	0
Hydrogen chloride	100	0	4	11	0	0	0	0	0	0	84	0	0	0
Iron	100	0	7	6	0	0	0	0	87	0	0	0	0	0
Kerosene	100	0	5	7	0	0	0	0	0	0	87	0	0	0
Lead	100	0	6	8	0	0	0	0	83	0	2	0	0	0
Limonene	100	0	100	0	0	0	0	0	0	0	0	0	0	0
Magnesium	100	0	0	98	0	1	0	0	0	0	0	0	0	0
Manganese	100	0	7	0	0	0	0	0	92	0	1	0	0	0
Mercury	100	0	5	10	0	0	0	1	0	0	85	0	0	0
Metals, unspecified	100	0	8	24	0	0	3	10	0	0	54	0	0	0

Methane	100	0	5	28	0	0	0	19	0	0	47	0	0	0
Methanol	100	89	2	9	0	0	0	0	0	0	0	0	0	0
Naphthalene	100	0	7	0	0	0	0	0	93	0	0	0	0	0
Nickel	100	0	3	58	0	1	0	0	27	0	11	0	0	0
Nitrogen dioxide	100	0	100	0	0	0	0	0	0	0	0	0	0	0
Nitrogen oxides	100	0	17	14	0	0	6	9	19	0	33	0	0	1
Nitrous oxide	100	0	100	0	0	0	0	0	0	0	0	0	0	0
NMVOC, non-methane volatile organic compounds,	100	0	12	40	1	0	5	25	0	0	16	0	0	0
Organic substances, unspecified	100	0	25	6	0	0	42	0	26	0	0	0	0	0
Particulates	100	94	6	0	0	0	0	0	0	0	0	0	0	0
particulates (unspecified)	100	0	100	0	0	0	0	0	0	0	0	0	0	0
Particulates, < 10 um	100	35	52	2	0	0	3	1	0	0	6	0	0	0
Particulates, < 2.5 um	100	0	0	98	0	1	0	0	0	0	0	0	0	0
Particulates, > 10 um	100	0	0	98	1	1	0	0	0	0	0	0	0	0
Particulates, > 2.5 um, and < 10um	100	0	0	97	1	1	0	0	0	0	0	0	0	0
Particulates, unspecified	100	0	5	9	0	0	0	1	0	0	85	0	0	0
Pentane	100	0	0	99	0	1	0	0	0	0	0	0	0	0
Phenol	100	0	99	0	0	0	0	0	0	0	0	0	0	0
Potassium	100	0	7	0	0	0	0	0	93	0	0	0	0	0
Sodium	100	0	7	6	0	0	0	0	87	0	0	0	0	0
Sulfur dioxide	100	0	4	80	15	1	0	0	0	0	0	0	0	0
Sulfur oxides	100	0	6	31	0	0	1	23	0	0	38	0	0	0
Toluene	100	0	0	99	0	1	0	0	0	0	0	0	0	0
Vanadium	100	0	0	99	0	1	0	0	0	0	0	0	0	0
VOC	100	0	0	100	0	0	0	0	0	0	0	0	0	0
VOC, volatile organic compounds	100	91	9	0	0	0	0	0	0	0	0	0	0	0
Zinc	100	0	7	2	0	0	0	0	91	0	0	0	0	0

			Input resources					Boiler fuels				Equipment fuels		
Emissions to water	**Total**	**MDF proc.**	**Furnish**	**UF resin**	**Wax**	**Urea scav.**	**Transpor**	**Nat. gas**	**Wood**	**DFO**	**Electricity**	**Nat. gas**	**Gas**	**Diesel**
Aluminum	100	0	0	73	26	0	0	0	0	0	0	0	0	0
Ammonia	100	0	10	21	0	0	4	12	0	0	53	0	0	0
Ammonium, ion	100	0	0	99	0	1	0	0	0	0	0	0	0	0
BOD5, Biological Oxygen Demand	100	0	3	74	2	0	1	13	0	0	8	0	0	0
Boron	100	0	5	8	0	0	0	1	0	0	87	0	0	0
Cadmium, ion	100	0	6	42	0	0	0	32	0	0	18	0	0	0
Calcium, ion	100	0	0	92	5	1	0	0	0	0	1	0	0	0
Chloride	100	0	6	44	0	0	0	31	0	0	18	0	0	0
Chromium	100	0	8	41	0	0	0	32	0	0	18	0	0	0
COD, Chemical Oxygen Demand	100	0	5	49	1	0	1	28	0	0	16	0	0	0
DOC, Dissolved Organic Carbon	100	0	0	98	1	0	0	0	0	0	0	0	0	0
Fluoride	100	0	97	0	0	0	0	0	0	0	3	0	0	0
Formaldehyde	100	0	0	100	0	0	0	0	0	0	0	0	0	0
Iron	100	0	5	7	0	0	0	0	0	0	88	0	0	0

			Input resources					Boiler fuels				Equipment fuels		
Emissions to water (continued)	**Total**	**MDF proc.**	**Furnish**	**UF resin**	**Wax**	**Urea scav.**	**Transpor**	**Nat. gas**	**Wood**	**DFO**	**Electricity**	**Nat. gas**	**Gas**	**Diesel**
Iron, ion	100	0	0	73	26	1	0	0	0	0	0	0	0	0
Lead	100	0	14	53	33	1	0	0	0	0	0	0	0	0
Magnesium	100	0	0	65	34	1	0	0	0	0	0	0	0	0
Manganese	100	0	5	7	0	0	0	0	0	0	88	0	0	0
Metallic ions, unspecified	100	0	24	46	1	1	15	1	0	1	12	0	0	1
Methanol	100	0	0	100	0	0	0	0	0	0	0	0	0	0
Nickel, ion	100	0	1	96	2	1	0	0	0	0	0	0	0	0
Nitrate	100	0	2	63	3	1	0	0	0	0	32	0	0	0
Nitrogen	100	0	0	99	0	1	0	0	0	0	0	0	0	0
Nitrogen, organic bound	100	0	0	99	0	1	0	0	0	0	0	0	0	0
Oils, unspecified	100	0	6	42	0	0	1	32	0	0	18	0	0	0
Organic substances, unspecified	100	0	6	38	0	0	0	29	0	0	26	0	0	0
Phenol	100	0	0	99	0	0	0	0	0	0	0	0	0	0
Phosphate	100	0	87	1	0	0	0	0	0	0	11	0	0	0
Phosphorus	100	0	0	100	0	0	0	0	0	0	0	0	0	0
Potassium, ion	100	0	0	57	43	1	0	0	0	0	0	0	0	0
Silicon	100	0	0	99	0	1	0	0	0	0	0	0	0	0
Sodium, ion	100	0	0	93	3	0	0	0	0	0	4	0	0	0
Solids, inorganic	100	0	0	99	0	1	0	0	0	0	0	0	0	0
Solved solids	100	0	6	42	0	0	0	33	0	0	18	0	0	0
Sulfate	100	0	6	38	0	0	0	25	0	0	31	0	0	0
Sulfuric acid	100	0	5	8	0	0	0	1	0	0	87	0	0	0
Suspended solids	100	100	0	0	0	0	0	0	0	0	0	0	0	0
Suspended solids, unspecified	100	0	5	14	0	0	0	14	0	0	66	0	0	0
TOC, Total Organic Carbon	100	0	0	98	1	0	0	0	0	0	0	0	0	0
Zinc, ion	100	0	6	47	7	0	0	25	0	0	14	0	0	0
Emissions to land														
Boiler fly ash	100	100	0	0	0	0	0	0	0	0	0	0	0	0
Wood waste	100	100	0	0	0	0	0	0	0	0	0	0	0	0
Waste														
Packaging waste, paper and board	100	0	100	0	0	0	0	0	0	0	0	0	0	0
Waste, inorganic	100	0	100	0	0	0	0	0	0	0	0	0	0	0
Waste, solid	100	0	8	13	0	0	0	6	1	0	72	0	0	0
Wood waste	100	0	100	0	0	0	0	0	0	0	0	0	0	0