This report is a combination of two reports:

1. SUMMARY REPORT: A LIFE CYCLE ANALYSIS OF CANADIAN SOFTWOOD LUMBER PRODUCTION, Prepared by Jamie K. Meil, Athena Sustainable Materials Institute, Ottawa, Canada, April 2000;

   and

2. RAW MATERIAL BALANCES, ENERGY PROFILES AND ENVIRONMENTAL UNIT FACTOR ESTIMATES: **STRUCTURAL WOOD PRODUCTS**, Prepared by Forintek Canada Corp., Ottawa, Canada, March 1993.

In this pdf, the earlier, original report follows directly after the more recent report.

the ATHENA™ Sustainable Materials Institute

SUMMARY REPORT:
A LIFE CYCLE ANALYSIS OF CANADIAN SOFTWOOD LUMBER PRODUCTION

Prepared by:

Jamie K. Meil
ATHENA™ SUSTAINABLE MATERIALS INSTITUTE

Ottawa, Canada
April, 2000

ACKNOWLEDGEMENTS

This report was made possible by the support of the Canadian Wood Council, Forintek Canada Corp. and the Canadian Forest Service. In particular, the author is indebted to Mr. John Burrows of the CWC for allowing the release of this report and information to the Institute's members ahead of their own full report.

DISCLAIMER

Although the ATHENA™ Sustainable Materials Institute has done its best to ensure accurate and reliable information in this report, the Institute does not warrant the accuracy thereof. If notified of any errors or omissions, the Institute will take reasonable steps to correct such errors or omissions.

COPYRIGHT

ATHENA™ Sustainable Materials Institute
112 Brock St. East, P.O. Box 189
Merrickville, Ontario, Canada, K0G 1N0
Tel: 613-269-3795
Fax: 613-269-3796
Email: wbtrusty@fox.nstn.ca

PREFACE

This summary report is a partial update to the October 1993 cradle-to-gate-life cycle inventory report on structural wood products. Specifically, it replaces chapter 5 of the1993 report describing the LCI results for softwood lumber, entitled "*Raw Material Balances, Energy Profiles and Environmental Unit Factor Estimates for Structural Wood Products*. This summary report has been prepared by the ATHENA™ Sustainable Materials Institute as part of a continuing program to maintain the currency of data used in ATHENA™, the Institute's systems model for assessing the relative life cycle environmental implications of alternative building or assembly designs.

The integration of all the Institute's life cycle inventory data is a primary function of ATHENA™ itself and we therefore caution that individual industry life cycle study reports may not be entirely stand-alone documents in the sense that they tell the whole story about an individual set of products. For example, the original wood products report and this summary report provide cradle-to-gate inventory data while other reports and databases cover the on-site construction, use, and demolition/disposal life cycle stages. ATHENA™ also generates various composite measures that can be best described as environmental impact indicators, a step toward the ultimate LCA goal of developing true measures of impacts on human and ecosystem health.

TABLE OF CONTENTS

A LIFE CYCLE INVENTORY OF CANADIAN SOFTWOOD LUMBER PRODUCTION

1.0 Introduction

This summary report presents a cradle-to-gate life cycle inventory for softwood lumber produced in Canada. It draws on a more exhaustive study report still undergoing a lengthy peer review process as part of the Canadian Raw Materials Database project (CRMD)[1], which the Institute has reviewed, and from which it has assembled this summary report for its members.

This softwood lumber database replaces an earlier version published in 1993 as Chapter 5.0 in our report entitled: "Raw Material Balances, Energy Profiles and Environmental Unit Factor Estimates for Structural Wood Products". The original data set was of a late '80s vintage, while this update is based on 1995 data. Further this new study augments the original in two other ways which will prove beneficial to the Institute's goals: (1) it expands the product profile to include green (unseasoned) lumber; not just kiln-dried lumber; and (2) the resource harvesting, transportation, and forest management activity stage can be used to update the resource extraction profile for the other softwood products in the ATHENA Model.

1.1 Report Structure

Section 2 of this report provides background information concerning the methodology used to develop the inventory data for softwood lumber. Section 3 then presents the final rolled-up inventory profile for both green and kiln-dried lumber.

2.0 Inventory Methodology

The CRMD study objective was to gather, analyze and generate a representative "cradle-to-gate" life cycle inventory (LCI) for the Canadian softwood lumber industry. Both green and kiln-dried softwood lumber product streams were studied from raw material extraction through product manufacturing, inclusive of all related transportation. The study was conducted in accordance with a previously developed and agreed to LCI methodology which complies with internationally agreed to LCI standards as set down by The International Organization for Standardization (ISO) in their Life Cycle Assessment Standards (ISO 14000 series).[2]

The study methodology drew on the Canadian Standards Association Z-760-94 Guideline; Life Cycle Assessment, the Society of Environmental Toxicology and

---

[1] A Life Cycle Inventory Report on the Production of Softwood Lumber in Canada, prepared by Roy F. Weston and JKM Associates for the Canadian Wood Council. Draft version completed November 1999. The goal of the CRMD study is to provide LCI data/databases for commodities produced by various material groups (steel, plastics, aluminum, glass, paper and wood products) to support voluntary improvements in the environmental performance of their products consistent with the Canadian Council of Ministers of the Environment (CCME) pollution prevention initiatives, and to perform screening LCI studies in making product and process design decisions.

[2] Canadian Standards Association 1995. Canadian Raw Materials Database: Life Cycle Inventory Methodology. Toronto, Ontario. 44 pp.

Chemistry's (SETAC's) A Technical Framework for Life-Cycle Assessment, SETAC's Guidelines for Life-Cycle Assessment: A "Code of Practice", and SETAC's Life-Cycle Assessment Data Quality: A Conceptual Framework. ATHENA's own Research Guidelines (LCI Methodology) conform to these same guidelines and standards.

This section highlights pertinent methodology aspects and their application to the softwood lumber industry.

2.1 Product System, Functional Unit and System Boundaries

The wood product systems studied included dry lumber and green lumber. The simplified process flow diagrams for each of these product systems are shown in Figures 2-1 and 2-2. The system function is to provide "cradle-to-gate" eco-profiles of dry and green softwood lumber. The functional unit for this study is to model one thousand board feet of lumber. The system's "envelope" or "boundary" includes the extraction of raw materials, materials processing, and manufacture. Each unit process, as depicted in Figures 2-1 and 2-2, is briefly described below.

Figure 2-1: Process Flow Kiln-Dried Diagram for Surfaced Lumber

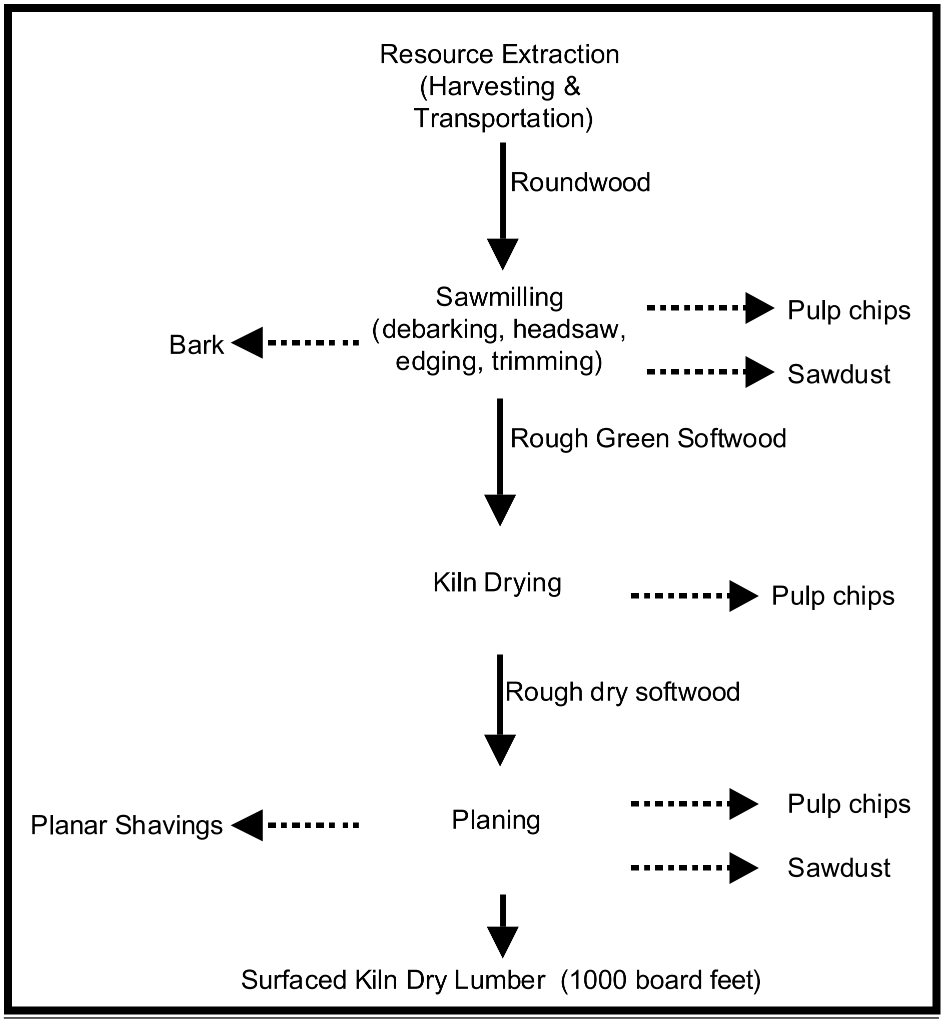
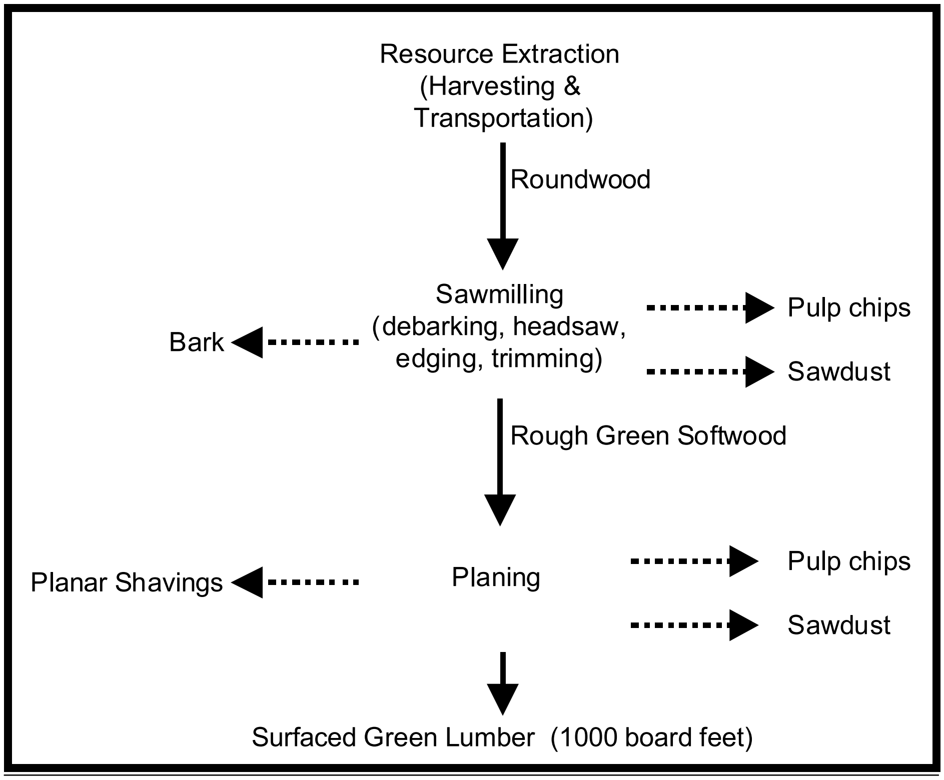


Figure 2-2: Process Flow Diagram for Surfaced Green Lumber



2.1.1 Resource Harvesting, Transportation & Management

The managed harvesting and regeneration of forests takes place in every province of Canada. Approximately 1 million hectares of forest is harvested annually by the forest industry. Canada loses a similar or greater amount of its forests to wildfire and insect infections every year. Over time, harvesting methods have become more mechanical and fiber transportation distances have increased. However, greater harvesting productivity and increased transportation capacities have tended to maintain historical energy use levels on a per unit basis.

Most planting and seeding activities are concentrated on sites that have been disturbed by fire, insects, disease or harvesting and had not regenerated on their own. Presently, most provinces rely more on natural regeneration.

The “resource extraction” unit process, as defined for this study, begins in the forest with the harvesting of trees. The operations associated with this unit process include:

- removal of trees as per an agreed management regime;
- transformation of the tree (delimbing) and forwarding to roadside;
- transportation of the tree lengths or bucked logs to the final mill destination;
- maintenance and repair of all logging and transportation vehicles and equipment; and
- site restoration and regeneration which may include (site preparation, planting, aerial seeding or natural regeneration).

The outputs from this unit process are logs or tree lengths (under bark solid wood - main product and bark - co-product) transported to the sawmill.

2.1.2 Sawmilling

This unit process begins with logs or tree-lengths in the mill yard. The operations associated with this unit process include:

- cutting to length of tree-lengths, sorting and storage of logs;
- debarking of the log input into the sawmill;
- breakdown of logs into rough lumber, pulp chips, and sawdust;
- maintenance and repair of all sawmill equipment and yard transportation vehicles;
- treatment of process air, liquids, and solids; and
- in yard conveyance of rough lumber, pulp chips and sawdust.

The output of this unit process is rough green lumber (main product), pulp chips (co-product), sawdust (co-product), and bark (by-product).

In the sawmill, raw logs are debarked and converted to rough green lumber and pulp chips. In the process, sawdust is produced. Each mill will have varying breakdown equipment and possibly a number of breakdown lines for processing different diameter logs. For example, a mill employing a small log line may use a chipper-canter machine center for producing pulp chips and a four or two-sided cant. On a large log line the mill may use a single or multi bandsaw configuration to produce a cant or rough dimension lumber with the exterior log slabs conveyed directly to an independent chipper breakdown center. Often squared cants are broken down further in multiple saw machine centers and are then edged and trimmed using sophisticated edger and trimmer optimizer machine center. Pulp chips, bark, and sawdust are collected from machine centers using gravity fed conveyance systems and stored in bins. The unit process ends with the sorting of rough green lumber by width, length and grade for sale or for further processing (i.e., planing in the case of surfaced-green lumber or kiln drying followed by planing in the case of surfaced-dry lumber).

2.1.3 Kiln Drying

This unit process begins with rough green lumber. The operations associated with this unit process include:

- conveyance of rough green lumber to a sticker-stacker;
- loading of stickered lumber stacks into a kiln facility;
- heat treatment and conditioning of lumber within the kiln;
- maintenance and repair of all kiln equipment and yard transportation vehicles;
- the treatment of process air, liquids, and solids; and
- unloading and conveyance of kiln-dried lumber to the planer mill.

The output of this unit process includes stickered rough kiln-dried lumber (main-product), and pulp chip furnish (co-product) delivered to the planer mill.

Drying is performed to lower the moisture content of lumber to levels appropriate for sale of construction grade lumber. The process of drying lumber down to the desired moisture level takes between 24 and 48 hours and is dependent primarily on the initial moisture content and species of lumber to be dried.

Kiln drying is by far the most energy intensive process in the production of surfaced-dry lumber, using about 90% of the thermal energy and 25% of the total mechanical (electrical) energy of the mill complex.

Kiln types and source fuels vary across the country. In Canada, over 50% of the process heat energy used to dry lumber is generated from burning hog fuel (bark, sawdust, planar shavings and fiber fines) produced on-site in the sawmill and planar mill. The utilization of biomass by-products has lessened the industry's dependence on fossil fuels.

Over the last ten years significant advances in computerized kiln-drying process control, on line sorting of lumber by species and moisture content and more efficient boiler technology has led to large reductions in energy required per unit of lumber. A thirty percent reduction in energy use is commonly reported.

2.1.4 Planing and Packaging

This unit process begins with either rough green lumber or stickered, rough kiln-dry lumber. The operations associated with this unit process include:

- de-stickering and/or unstacking of lumber;
- planing (surfacing) of lumber;
- trimming, grading and sorting of lumber;
- stacking, strapping and packaging of lumber;
- maintenance and repair of all planer equipment and associated yard transportation vehicles; and
- treatment of process air, liquids and solids.

The output of this unit process is surfaced and packaged lumber (main product) by type, size and grade as well as planer shavings (co-product), sawdust (co-product) and pulp chip furnish (co-product).

Lumber is planed to achieve four smooth sides and the final dimensions of the commodity product. Final trimmings to length and grading are also part of the process. The lumber is then solidly stacked and packaged according to customer specifications or for inventory.

The planer itself is the most energy intensive piece of equipment in the planar mill with an electric motor in the 200 H.P. range. Saw dust and planar shavings are collected for either sale or as hog fuel furnish for the kiln drying boiler. Trim ends are also collected and sent to the chipper for manufacture into pulp chips for sale.

2.2 Geographic and Time Period coverage

In accordance with the CRMD Methodology, the initial analysis step was to define the domain for the study based on geographic sources of supply of Canadian softwood lumber.

There are over 1100 Canadian manufacturers of softwood lumber which precludes any attempt to undertake a plant-by-plant analysis. In the interest of cost effectiveness and representativeness, it was more prudent to concentrate the survey on the larger regional mill segments producing the majority of lumber. As a result, the variability in scale economies and technology across the industry was minimized. Industry data indicates that mills producing over 50 million board feet (MMBF) and employing over 100 person-years annually are the major producers of softwood lumber in Canada. As agreed among the CRMD technical committee, the goal was to sample between 20 and 25 of these larger mills (5% of the 390 largest mills which produce about 95% of all softwood lumber in Canada). Twenty-two mills were contacted to participate in the study. These mills were purposely selected to proportionally reflect regional production totals. For example, British Columbia coastal mills account for 15% of total Canadian production and hence 4 mills producing over 50 MMBF per year from this region were sampled. The domain for this study therefore included facilities from the various geographic regions in Canada with similar production weights as shown in Table 2-1. All the primary data provided, was from the calendar year 1995.

Table 2-1: Domain and Geographical Coverage

Geographical Regions	% of Canadian Production	No. of Mills Sampled	% Production of Sampled Mills
B. C. Coast	15%	4	17%
BC Interior/Alberta	52%	8	48%
Ontario	12%	4	14%
Quebec	21%	6	21%
	100%	22	100%

2.3 Data Collection

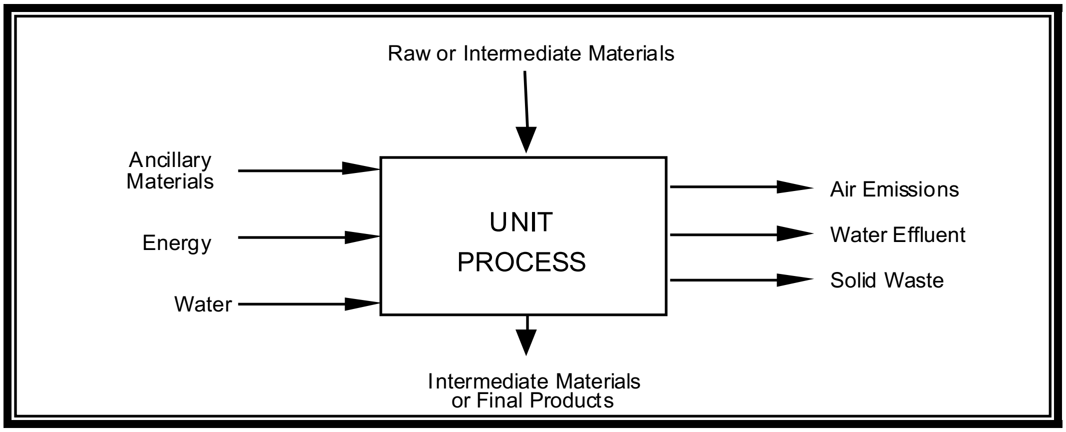
The primary sources of data for this study are the responses to a set of questionnaires (Data Inventory Sheet[3] or DIS) that were prepared and distributed to 22 mills in Canada. These questionnaires were sent out in early Fall of 1996 and returned over the next 6 months. All the data collected was for the 1995 calendar year.

Each unit process in the system is characterized and documented by a list of input materials, energy and emissions as shown in Figure 2-3. The primary source of data was from the questionnaires prepared and issued to the participating companies. In all, the study drew on completed questionnaires for 88 separate unit processes. A description of the manner in which the data obtained from the survey was processed (allocated, aggregated, etc.) is provided in the following section.

---

[3] Unit process Data Inventory Sheets (DISs) and a DIS questionnaire guide were custom developed for this project by Roy F. Weston, Inc. and JKM Associates.

Figure 2-3: Life Cycle Inventory Unit Process Template



2.4 Calculation Procedures

In addition to numerous assumptions made to simplify the data collection process, several special calculation procedures were used to refine and integrate the information in the inventory. This section will briefly describe the techniques and calculations used in completing the inventory.

2.4.1 Reporting Units

All material and water consumption, as well as environmental emissions, were converted to metric units - mass in kilograms (kg); volume in liters (L); gaseous volume in cubic meters (Cu. M); surface area in square meters (Sq. M); and energy in mega-joules (MJ).

2.4.2 Allocation Procedures

Allocation procedures are used to partition inputs and/or outputs within a specific product system. An allocation procedure is required when a unit process within a system shares a common pollution treatment infrastructure or where multiple products or co-products are produced in a common unit process. When necessary, co-product allocations were performed on a mass basis.

For allocation of utilities and services common to several processes, allocations were made to reflect relative use of the service. For example, in instances where different unit processes (kiln drying and saw milling) shared the same effluent treatment facilities, allocation was determined by the percent of treatment load generated by each process.

Similar techniques based on mass of the unit process outputs were used to allocate some common solid waste streams like general refuse. When different unit processes shared a common energy source, for example an electric grid, the metered energy to a specific unit process was used to allocate the common use items like plant and office lighting or space heating.

2.4.3 Ancillary Material Analysis

The following decision rule process was employed for completing this analysis:

1. All potential ancillary material flows for a unit process that are greater than 1% by mass of the output of the unit process are first identified. Once the ancillaries have been identified, a mass balance for the sub-systems being analyzed is performed and normalized to the output from the sub-system.

2. Ancillary materials are then classified for inclusion in the scope of the study based on an analysis of their contribution to the mass of the sub-system, energy of the sub-system and their environmental relevance.

3. All ancillary materials of a ranked ancillary list, which have a cumulative mass contribution of up to 95% of the sub-system, are included in the scope of the study.

4. A further decision rule is used to classify energy contribution. All ancillary materials that have a cumulative contribution of 99% of the total sub-system energy are included in the scope of the study, regardless of their mass ranking.

5. The remaining ancillary materials that are not selected as a result of the mass and energy criteria are analyzed for their environmental relevance. Specifically, an analysis is performed to determine if the ancillary material flow contributes more that 15% to an environmental release data category.

Based on the above decision rules, there were no ancillary contributions to the product systems.

2.5 Secondary Data Sources and Integration

Primary data for separate facilities concerning the same product or process were averaged and presented in a fashion that ensures confidentiality of individual company data. These aggregated results (weighted-average numbers normalized for each unit process) will be published in CWC's detailed report and are not duplicated here. Instead, the remainder of this section describes additional data and integration procedures used to generate the results for the dry and green lumber product system rollup.

2.5.1 Emissions from Fuel

This study assumes that energy values used are characteristically the same as fuels extracted in North America. The environmental releases from the combustion of these fuels are shown in Appendix A. The values in this appendix include the pre-combustion energy for these fuels. Their emissions are added to the process emissions in the product system rollup. This study used values from the WESTON[4] databases.

---

[4] Roy F. Weston, Inc provided data rollup services for this study.

2.5.2 Electrical Energy

The mix of energy sources, electricity generation efficiency, transmission losses, and environmental releases were determined for the average Canada National Grid from the CRMD methodology document. The energy mix, environmental releases, and the energy requirements (including pre-combustion factors) to deliver one Kilowatt-hour (kWh) of electricity are presented in Appendix B.

2.5.3 Transportation Energy

The four modes of transportation identified in this study are truck, rail, barge, and ocean vessel. The environmental releases and the energy requirements (including pre-combustion factors) to deliver one metric tonne-kilometer (tonne-km) for each of the transport modes are presented in Appendix C. Estimates of distance and mode of travel were provided by the reporting locations.

2.5.4 Feedstock Energy

Feedstock energy is defined as the energy content of material resources. It is calculated as the gross calorific value (high heat) of the energy resources removed from the earth's energy reserves. It is the calorific value of the inputs to the system as opposed to the calorific value of the output. This study used values from WESTON databases and does not attach a feedstock value to wood fiber which coincides with ATHENA's treatment of wood fiber feedstock value.

3.0 Product System Rollup Results

3.1 Results Overview

This section quantifies material, energy, and water consumption and environmental burdens of green and kiln-dried lumber product systems. Each product system includes the raw material acquisition, processing, and product manufacture life cycle stages. This type of study is commonly referred to as a cradle-to-gate life cycle inventory. The material inputs and outputs for either product system beyond the plant gate have not been quantified and are not included in these results.

The inputs to the product systems include raw material (material consumption) and energy inputs (energy consumption). Material consumption includes the consumption of minerals, water, and petrochemical feedstocks. Energy consumption includes the use of energy at the plant (purchased/self-generated), energy used in transportation of raw materials, products and solid waste, and pre-combustion energy (energy expended to extract, refine, and deliver a fuel).

The outputs of these two product systems are emissions to air, water and land. The air emissions quantified include dust & particulates (includes metals), CO_2, CO, SO_x, NO_x, non-methane hydro-carbons (includes halogenated organic compounds), CH_4, acid gases (HCl and HF), and lead (Pb). The quantified emissions to water include dissolved solids, suspended solids, heavy metals, oils & greases, other organics, and phosphates & ammonia. The solid waste produced by the product system was aggregated based on the waste management method used. Waste management options include landfilling, recycling, incineration, and beneficial use.

Tables 3-1 through 3-6 summarize the 'cradle-to-gate' profiles of the 'rough green lumber' and 'kiln dried lumber' product systems.

Table 3-1: Energy Consumption for Lumber Products

Energy Consumption– per 1000 Board Ft. of Lumber			
	Units	**Dry Lumber**	**Green Lumber**
Process – Non-electric	**MJ**	**2,174**	**645**
Fuel Oil	MJ	18	2
Diesel	MJ	391	369
Gasoline	MJ	38	36
Natural Gas	MJ	522	34
Hog Fuel	MJ	1,194	195
Propane	MJ	12	8
Process - Electric	**MJ**	**526**	**399**
Transportation	**MJ**	**96**	**94**
Total	**MJ**	**2,795**	**1,138**

Table 3-2: Net Water Usage for Lumber Products

Net Water Use – per 1000 Board Ft. of Lumber			
	Units	**Dry Lumber**	**Green Lumber**
Process	L	43	23
Fuel Related	L	8	7
Total	**L**	**51**	**30**

Table 3-3: Raw Material Consumption for Lumber Products

Raw Material Consumption– per 1000 Board Ft. of Lumber			
	Units	**Dry Lumber**	**Green Lumber**
Primary Material			
Wood Fiber	kg	6.33E+02	6.33E+02
Ancillary Materials			
Hydraulic Fluids	L	2.69E-01	2.5E-01
Greases	kg	4.78E-02	4.56E-02
Motor Oils	L	1.75E-01	1.68E-01
End Paint	L	1.08E-02	1.08E-02
Polyethylene Plastic	kg	5.45E-04	5.45E-04
Lumber Wrap	kg	1.39E-01	1.39E-01
Steel Strapping	kg	4.58E-01	4.58E-01

Table 3-4: Air Emissions for Lumber Products

Air Emissions by Pollutant – per 1000 Board Ft. of Lumber			
	Units	**Dry Lumber**	**Green Lumber**
Particulate Matter	Kg	9.51E-01	2.05E-01
CO	Kg	6.27E-01	5.71E-01
CO2 (Total)	Kg	1.82E+02	7.04E+01
CO2 (Biomass)	kg	9.73E+01	1.59E+01
SOx	Kg	2.33E-01	1.83E-01
NOx	Kg	9.52E-01	6.46E-01
Non-Methane Hydrocarbons	Kg	2.57E-01	1.07E-01
Methane	Kg	4.31E-02	3.05E-02

Table 3-5: Water Effluents for Lumber Products

Water Effluents by Pollutant – per 1000 Board Ft. of Lumber			
	Units	**Dry Lumber**	**Green Lumber**
BOD	Kg	3.10E-03	3.05E-01
CO	Kg	6.27E-01	5.71E-01
CO2 (Total)	Kg	1.82E+02	7.04E+01
CO2 (Biomass)	kg	9.73E+01	1.59E+01
SOx	Kg	2.33E-01	1.83E-01
NOx	Kg	9.52E-01	6.46E-01
Non-Methane Hydrocarbons	Kg	2.57E-01	1.07E-01
Methane	Kg	4.31E-02	3.05E-02

Table 3-6: Solid Waste Emissions and Solid Waste Management for Lumber Products

Solid Waste – per 1000 Board Ft. of Lumber			
	Units	**Dry Lumber**	**Green Lumber**
Total Process Waste	kg	20.8	20.0
Municipal	kg	0.2	0.2
Total Solid Waste	**kg**	**20.9**	**20.2**
Solid Waste Management – per 1000 Board Ft. of Lumber			
	Units	**Dry Lumber**	**Green Lumber**
Landfilled	kg	18.1	17.4
Incinerated	kg	2.7	2.7
Recycled	kg	0.1	0.0
Beneficial Use	kg	-	-
Total Solid Waste	**kg**	**20.9**	**20.1**

3.2 Results Discussion

This summary report describes the “cradle-to-gate” environmental burdens associated with the production of green and kiln-dried lumber in Canada. The study was conducted using the methodology purposely developed for the Canadian Raw Material Database Initiative which basically conforms to the Institute’s own Research Methodology Guidelines. Twenty-two of Canada’s largest softwood lumber mills participated in the study and provided raw life cycle inventory data for 88 unit processes used to complete the study.

Final roll-up results indicate that both product systems’ resource utilization is very high with less than 4% of the wood and bark fiber going to landfill. The most significant difference between green and dry softwood lumber production is their respective energy use, with green lumber only 40% as energy intensive as kiln-dried lumber. Consequently, air emissions were greater for kiln-dried lumber than for the green lumber product system. Emissions to water were found to be quite low for both product systems and for the most part, can be attributed to the production of purchased electricity.

Compared to the Institute’s published1993 LCI results for kiln-dried softwood lumber, this study indicates a 24% improvement in cradle-to-gate energy efficiency. In addition, biomass energy consumption has increased by 8% reducing the industry’s dependence on non-renewable energy sources. But because of the disparities between the mill samples across the two studies, in both sample size and scale of operations for the mills included, the significant improvement in energy efficiency can only be in part attributed to technical change within the industry. However, the recent sample is more indicative of the portion of the industry which provides 95% of the softwood lumber in Canada.

Appendix A - Fuel Emission Factors

(per unit of fuel input inclusive of precombustion burdens)

	H. Fuel Oil kg	Diesel Litre	Gasoline Litre	Natural Gas M3	Propane Litre	Coal kg
WATER USE litres	1.2E-01	1.02E-01	1.04E-01	2.32E-07		3.54E-04
AIR EMISSIONS **kg**						
Particulate Matter	3.3E-03	1.58E-03	2.38E-03	4.92E-05	2.41E-04	1.3E-03
CO	9.00E-04	1.27E-02	9.41E-01	6.64E-04	1.33E-03	6.87E-03
CO2	3.86E+00	3.05E+00	2.86E+00	1.97E+00	1.62E+00	2.65E+00
SOx	4.78E-02	3.71E-03	5.58E-03	1.86E-02	2.25E-03	1.53E-02
NOx	8.45E-03	4.75E-02	2.57E-02	9.01E-03	9.16E-03	7.74E-03
Non-CH4 Hydrocarbons	1.03E-03	2.24E-03	4.72E-02	2.38E-05	2.77E-03	8.08E-04
CH4						
WATER EFFLUENT **kg**						
BOD	4.07E-04	3.44E-04	7.85E-04	9.76E-10		1.17E-06
COD	0	0	0	0		0
Heavy Metals	0	0	0	0		0
Other Organics						
Suspended Solids	1.85E-03	1.56E-03	3.56E-03	4.43E-09		5.3E-06
Dissolved Solids	0	0	0	0		0
Oil and Grease	2.34E-04	1.98E-04	35.6E-03	4.43E-09		5.3E-06
Phosphates						
NH4+	0	0	0	0		0
SOLID WASTE **kg**	1.71E+00	1.45E+00	1.28E+00	3.48E-06		2.35E-01

References:

Energy Information Administration. Coal Industry annual 1995. DOE/EIA-0854(95).

Energy Information Administration. Petroleum Supply Annual 1995. (Volume 1) DOE/EIA-0340(95)/1. May 1996

Energy Information Administration. Natural Gas Annual 1995. DOE/EIA-0131(95) Nov. 1996

US EPA Compilation of Air Pollutant Emission factors, AP-42, Fifth Edition, Volume 1: Stationary Point and Area Sources

Appendix B – Electricity Emission Factors

(per kWh delivered inclusive of precombustion burdens)

	National Grid
WATER USE litres	5.22E-05
AIR EMISSIONS **kg**	
Particulate Matter	2.50E-04
CO	5.12E-05
CO2	2.84E-01
SOx	2.01E-03
NOx	9.92E-04
Non-CH4 Hydrocarbons	5.22E-05
CH4	
WATER EFFLUENT **kg**	
BOD	2.64E-07
COD	0
Heavy Metals	0
Other Organics	5.84E-04
Suspended Solids	1.10E-04
Dissolved Solids	1.16E-03
Oil and Grease	0
Phosphates	0
NH4+	0
SOLID WASTE **kg**	1.15E-02

Appendix C – Transportation Emission Factors

(per tonne-km inclusive of precombustion burdens)

MODE	Units	Heavy Truck Diesel	Rail Diesel	Barge Diesel	Ocean Vessel Fuel Oil
FUEL CONSUMPTION	MJ/t-km	1.04E+00	3.35E-01	3.42E-01	9.72E-02
WATER USE	Liters/MJ	3.4E-03	3.4E-03	3.53E-03	3.53E-03
AIR EMISSIONS					
Particulate Matter	kg/MJ	1.58E-03	2.38E-03	4.92E-05	2.41E-04
CO	kg/MJ	1.27E-02	9.41E-01	6.64E-04	1.33E-03
CO2	kg/MJ	3.05E+00	2.86E+00	1.97E+00	1.62E+00
SOx	kg/MJ	3.71E-03	5.58E-03	1.86E-02	2.25E-03
NOx	kg/MJ	4.75E-02	2.57E-02	9.01E-03	9.16E-03
Non-CH4 Hydrocarbons	kg/MJ	2.24E-03	4.72E-02	2.38E-05	2.77E-03
CH4	kg/MJ	5.53E-05	5.27E-05	5.03E-05	5.03E-05
Lead	kg/MJ	1.60E-09	1.60E-09	1.67E-09	1.67E-09
HCL	kg/MJ	5.97E-07	5.97E-07	6.21E-07	6.21E-07
HF	kg/MJ	7.47E-08	7.47E-08	7.76E-08	7.76E-08
WATER EFFLUENT					
BOD	kg/MJ	1.15E-05	1.15E-05	1.2E-05	1.2E-05
COD	kg/MJ	9.73E-05	9.73E-05	1.01E-04	1.01E-04
Heavy Metals	kg/MJ	7.38E-07	7.38E-07	7.67E-07	7.67E-07
Other Organics	kg/MJ				
Suspended Solids	kg/MJ	5.22E-05	5.22E-05	5.44E-05	5.44E-05
Dissolved Solids	kg/MJ	1.38E-03	1.38E-03	1.44E-03	1.44E-03
Oil and Grease	kg/MJ	6.63E-06	6.63E-06	6.89E-06	6.89E-06
Phosphates	kg/MJ				
NH4+	kg/MJ	1.68E-06	1.68E-06	1.75E-06	1.75E-06
SOLID WASTE	kg/MJ	4.85E-02	4.85E-02	5.04E-02	5.04E-02

the ATHENA™
Sustainable Materials Institute

RAW MATERIAL BALANCES, ENERGY PROFILES AND ENVIRONMENTAL UNIT FACTOR ESTIMATES:

STRUCTURAL WOOD PRODUCTS

Prepared by:

Forintek Canada Corp.

Ottawa, Canada
March, 1993

DISCLAIMER

COPYRIGHT

ATHENA™ Sustainable Materials Institute
112 Brock St. E., P.O. Box 189
Merrickville, Ontario Canada, K0G 1N0
Tel: 613-269-3795
Fax: 613-269-3796
Email: wbtrusty@fox.nstn.ca

TABLE OF CONTENTS

PREFACE

1.0 INTRODUCTION

3.0 INDUSTRY ENVIRONMENTAL ISSUES/CONSIDERATIONS

4.0 FOREST HARVESTING, ROUNDWOOD TRANSPORT & FOREST MANAGEMENT

5.0 KILN DRIED SOFTWOOD LUMBER

6.0 SOFTWOOD PLYWOOD

7.0 ORIENTED STRAND BOARD (OSB) / WAFERBOARD (WB)

8.0 ENGINEERED WOOD PRODUCTS

LIST OF TABLES

LIST OF APPENDICES

Preface

This report was originally published as part of the ATHENA™ project, initiated in 1990 by Forintek Canada Corp. with the support of Natural Resources Canada, under the name *Building Materials in the Context of Sustainable Development*. Work on the ATHENA™ project is now being carried forward by the ATHENA™ Sustainable Materials Institute, a not-for-profit organization dedicated to helping the building community meet the environmental challenges of the future.

The ultimate goal is to foster sustainable development by encouraging selection of the material mix that will minimize a building's life cycle environmental impact. To achieve that goal, the Institute is developing ATHENA™, a systems model for assessing the relative life cycle environmental implications of alternative building or assembly designs. Intended for use by building designers, researchers and policy analysts, ATHENA™ is a decision support tool which complements and augments other decision support tools like costing models. It provides a wealth of information to help users understand the environmental implications of different materials mixes or other design changes in all or part of a building.

From the outset, the project brought to bear the combined talents of architects, economists, engineers and environmentalists in a research alliance which included the following university programs, government agencies and private firms, many of which continue to contribute to the Institute as advisory members or researchers:

- CANMET, a division of Natural Resources Canada;
- Environmental Policy Research, Trent University;
- Environmental Research Group, University of British Columbia School of Architecture;
- Forintek Canada Corp.;
- JKM Associates;
- Steltech Ltd. (formerly a subsidiary of Stelco, now part of Hatch Associates);
- The Centre for Studies in Construction, University of Western Ontario;
- Venta, Glaser & Associates; and
- Wayne B. Trusty & Associates Limited.

The ATHENA™ Institute is continuing the practice of publishing all individual research reports and major progress reports to make the process as transparent as possible and to ensure the research and results are fully accessible. To ensure continuity, previously published reports such as this one are being reissued as part of the Institute series.

Institute studies and publications fall into two general categories: investigative or exploratory studies intended to further general understanding of life cycle assessment as it applies to building materials and buildings; and individual life cycle inventory studies which deal with specific industries, product groups or building life cycle stages. All studies in this latter category are firmly grounded on the principles and practices of life cycle assessment (LCA), and follow our published Research Guidelines, which define boundary or scope conditions and ensure equal treatment of all building materials and products in terms of assumptions, research decisions, estimating methods and other aspects of the work. The integration of all inventory data is a primary function of ATHENA™ itself. ATHENA™ also generates various composite measures that can best be described as environmental impact indicators, a step toward the ultimate LCA goal of developing true measures of impacts on human and ecosystem health.

We believe this report and others in the series will be of value to people concerned with the environmental implications and sustainability of our built environment. But we caution that individual industry life cycle study reports may not be entirely stand-alone documents in the sense that they tell the whole story about an individual set of products. For example, the report on concrete notes how much steel is used for reinforcing various products, but the life cycle inventory data for those steel products is included in the reports dealing with integrated and mini-mill steel production. There are also transportation and energy production and distribution aspects that are common to many different building products and are therefore handled separately within ATHENA™.

Please contact us at the address shown on the page following the cover for more information about the ATHENA™ Sustainable Materials Institute or other reports in the series.

RAW MATERIAL BALANCES, ENERGY PROFILES & ENVIRONMENTAL UNIT FACTOR ESTIMATES FOR STRUCTURAL WOOD PRODUCTS

1.0 INTRODUCTION

This report summarizes material and energy balances for the extraction and manufacture of a number of structural wood products. The list of structural wood products considered includes traditional as well as relatively new engineered wood products. These structural products are:

- kiln-dried softwood lumber
- structural plywood sheathing
- oriented strand board (OSB) sheathing
- parallel strand lumber (PSL)
- laminated veneer lumber (LVL)
- composite wood "I"-joists
- parallel and pitched chord light frame trusses
- composite wood/steel open web joists

The information contained in this report was gathered from many published sources as well as proprietary data bases and knowledgeable people from a variety of industrial operations.

1.1 Analysis Level and Scope

Evaluating a product's embodied energy, resource use efficiency and environmental impact is a complex undertaking with few absolutes, which makes any one figure contestable. The energy, resource, and environmental measures quoted in this report are of a "typical" plant nature and should not be construed as being applicable to a specific plant in a particular location.

To ensure consistent and compatible approaches by the different alliance members, all estimates had to be prepared in accordance with a set of research guidelines issued in October 1992. This research protocol defined information requirements and procedures for the study, such as the following:

- the specific building products:
- the content of general and detailed industry descriptions;
- the specific energy forms, emissions and effluents of interest;
- the treatment of secondary building components and assemblies;

- preferred data sources(e.g. actual industry data and data from process studies);
- the analysis scope, including system boundaries and limits and the level of detail of the analysis;
- geographic divisions;
- transportation factors to be included when estimating transportation energy use; and
- a set of standard conventions for dealing with such aspects as non-domestic production, process feedstocks, in-plant recycling and multiple products.

The Research Guidelines report is available under separate cover[1] as part of the full set of project reports and we have not, in this report, duplicated that material by explaining the rationale for all the steps in the research and calculation process. Some of the salient study aspects are discussed below.

To maintain a level of comparability among the different wood products and their non-wood brethren, quantities of products are reported in oven-dry (O.D.) metric tonnes. With the exception of softwood lumber, the other wood products contained in the report are comprised of both wood and adhesives. During analysis these two raw material input streams are kept separate and then later combined to arrive at the final product. Where adhesives comprise 5% or less of the total product weight, these amounts have been added to the final product; i.e., a product containing 1% adhesive by weight would have a final oven dry weight of 1.01 tonnes. Appropriate conversion factors to saleable product quantities are also provided.

To maintain uniformity in expressing energy requirements and consumption, all energy measures are reported in gigajoules (Gj) for all products. For purchased energy, the actual gross energy used at the mill site is reported with no allowance for how the energy was produced or transported to the site. Process heat energy converted on site via burning of wood waste (hogfuel) or fossil fuels takes into consideration the industrial burning efficiency of the fuel at the site. Gross energy use is stated throughout the report.

Wood product production more often than not results in a number of different products being produced simultaneously. For example, in the process of producing softwood lumber, pulp chips, planer shavings, sawdust and bark are also produced and segregated. Where these products are forwarded on as input into another process (e.g. pulp chips into pulp) the initial impacts incurred in their production must be allocated to the eventual final product. This is referred to as coproduct allocation. Where coproducts exist we have allocated their impact on the basis of weight and deducted any subsequent impact from the product of interest.

---

[1] for a complete discussion of the project's research methodology see Building Materials in the Context of Sustainable Development: Research Guidelines Report. Available from Forintek Canada Corp.

The material and energy balance estimates provided have been developed in accordance with Level II analysis boundaries as stipulated by the International Federation of Institutes of Advanced Studies (IFIAS), which typically captures 90% to 95% of the full energy impacts of an industry. Similarly, the calculated environmental emissions reflect this same level of analysis.

Air emissions include both energy and process related emissions and have been developed using the emission factors reported in Appendix A. At this writing the research alliance has not adopted a standard database for air emissions from the use of purchased electricity. For this reason, emissions associated with the reported electricity use have not been tabulated. These electricity emission figures will be incorporated into this report and the computer model at a later date.

Distance and mode of transport factors have been fully developed for raw materials delivered to mills and finished products to final end use markets. Finished product transportation factors are reported in Appendix B. The reported air emissions account for raw material delivery and intermediate wood product transport to secondary processing plants. Air emissions associated with finished product delivery to final markets have not been tabulated here as these are determined by the building location. These finished product transportation air emissions will also be generated by the model for each of the major urban centres.

The remainder of this report is structured in the following manner:

Section 2 provides a brief wood products industry overview: the size and scope of the industry in a national context as well as significant technology developments in processing and end use efficiency of wood products.

Section 3 describes a number of pollution abatement issues confronting the industry and underscores the assumptions and limits unique to this analysis.

Section 4 quantifies the energy required to extract and deliver roundwood to a wood products manufacturing facility.

Sections 5, 6, 7, and 8 presents a discussion and summary of material, energy and emission profiles for softwood lumber, plywood, oriented strand board and a number of engineered wood products respectively.

2.0 WOOD PRODUCTS INDUSTRY OVERVIEW

Due to Canada's rich endowment of forest resources, the wood products industry has long been one of the country's leading industrial sectors. In terms of timber supply, wood product production and world trade in primary wood products (sawn wood and wood based panels), Canada continues to play an immensely important role. About 12% of the world's closed forest area and 15% of global coniferous timber resources lie within Canada's border. In 1990, Canada produced 11 percent of the world's industrial roundwood, 12% of the world's supply of sawn wood and 5% of the total world supply of wood based panels.

In 1990, the primary wood products industry's value of shipments approached 7.5 billion dollars, of which $5.8 billion worth was exported to markets around the world. Because Canada is a large net exporter of primary wood products, the industry contributes positively to Canada's trade balance. The 1990 merchandise trade balance for primary wood products was $5.3 billion or about half of Canada's total net merchandise trade balance. Engineered wood product production in Canada is primarily destined for use by the domestic construction sector. The value of domestic shipments for the engineered wood products sector is estimated to be $1.5 billion. The primary and engineered wood product industries are a major industrial sector in terms of sales, employment, export earnings and contribute positively to Canada's trade balance and hence, the standard of living enjoyed by all Canadians.

Over its long history the wood products industry has made substantial changes in its applied manufacturing technology to improve both its cost performance and its utilization of the available resource. These improvements are difficult to measure due to the length of time it takes technology to diffuse through this diverse industry. In addition, the changing size and composition of the resource base overtime makes it difficult to determine a benchmark from which progress can be measured. The following listing describes a number of these technological changes in the manufacture of wood products and their general impact on the industry's efficiency.

- the adoption of thin kerf saws to increase fibre recovery
- the use of predetermined sawing patterns for specific log diameters to better match the resource to the desired product and reduce fibre losses
- sorting of wood by species and moisture content prior to breakdown to reduce process heat needs in drying
- spindless lathes allow greater veneer recovery and utilization of smaller logs
- new knife materials and feedback controls reduces fibre loss in the manufacture of wafers and strands from previously underutilized species

These are but some of the technological process improvements that have taken place overtime in the production of traditional structural wood products. New engineered products have also been developed. This product subset offers predetermined and uniform performance often with the use of less fibre input. The development of non-structural composite panels has further increased the use of the by products of structural wood product production; thereby, reducing the overall solid waste produced.

Not all the technology improvement has occurred in the production of wood products, as much or arguably more has taken place in the utilization of new and traditional wood products over time. This in-use efficiency evolution of wood products is perhaps best illustrated by changes evident in the residential construction sector. Prior to World War II milled lumber was held together with a top plate and sill plate and then panelled on the exterior side with boards and on the interior with lathe and plaster of the house. Since then, the amount of wood in a stick-frame house has been steadily on the decrease due to more efficient building methods which have led to more effective utilization of both traditional as well as new wood building products. Not only has dimensional framing lumber been shrinking - a 2x4 is no longer 2 inches by 4 inches, but floors which used to be planked, then overlaid with hardwood are now covered with plywood or oriented strand board and topped with carpet or vinyl flooring. Roofs used to be supported with full 2x10 framing rafters; now roofs rest on light frame lumber trusses that rely more on design loads than on excessive lumber thickness. Drywall has replaced lathe and plaster and resource efficient sheathing panels have replaced exterior board sheathing.

3.0 INDUSTRY ENVIRONMENTAL ISSUES/CONSIDERATIONS

3.1 Energy Conservation

Longer hauling distances and increased mechanization of logging operations have made it difficult for the industry to decrease energy consumption in the process of extracting and delivering roundwood to the primary mill. However, relative to a number of alternative structural building materials, the manufacture of primary structural wood products is neither particularly energy intensive nor is the cost of energy a major industry performance determinant. A considerable portion of the process energy required for the manufacture of wood products is derived directly from by-products. In fact, numerous studies have indicated that sawmills, plywood and OSB mills could be totally energy self-sufficient using only their biomass by-products to produce both their electricity and process heat needs. Currently, full energy self-sufficiency has yet to be realized as traditional fuel costs have not risen to levels that would warrant the capital expenditures associated with full conversion to biomass energy. Still Canadian mills have made great strides in energy conservation. The Canadian Industry Program for Energy Conservation reports a 7% improvement in energy efficiency for the B.C. industry since 1985.

Given their relative short history, little or no energy conservation performance measures are available for engineered wood products manufacture. Generally, composite lumber (PSL & LVL) and panel products (OSB) are more energy intensive than plywood or sawn lumber. But the assembly and lay-up of composite joists and trusses is even less energy intensive than lumber and plywood manufacture.

3.2 Pollution Abatement

3.2.1 Particulate Emissions

In primary wood product production the heat for drying and curing products is the largest energy aspect in the manufacturing process. Much of this process heat is derived from the burning of wood waste biomass, which is unique to the forest products industry. The result is that wood products production is less dependent on fossil fuels and contributes less to the draw down of these limited reserves. The burning of wood waste (hogfuel) however, does present some unique environmental challenges. Prior to wood waste utilization as a fuel source, it was common practice to burn such waste in conical bee-hive type burners to reduce the amount of material having to be landfilled. This practice has almost come to a halt across the country due to the amount of dense smoke and soot (particulates) released by this inefficient disposal burning method. Particulate emissions, however, remain a concern for those using wood waste as a fuel source. Particulate pollutants are primarily fly-ash and unburned carbon. Numerous systems in use today effectively remove particulates from the stack gases. Cyclone and multi-cyclone particulate control systems are in wide spread use across the wood products industry and are capable of removing as much as 94% of the particulates emitted (Anderson and Tillman, 1977). Below is a listing of average stack emissions resulting from the industrial burning of one Mj of wood waste.

Table 1
AVERAGE EMISSION FACTORS FOR INDUSTRIAL WOOD WASTE BURNING
(g/Mj)

ELEMENT	(g/Mj)
Particulates	0.7076
Sulphur dioxide	0.0022
Nitrogen oxide(s)	0.1130
Volatile organic compounds	0.0567
Methane	0.0121
Carbon monoxide	0.0111
Carbon dioxide	81.5000

Sources: Emission factors for green house gases by fuel type: an inventory, Energy, Mines and Resources Canada, Ad Hoc Committee on Emission Factors (Dec./90).
U.S.E.P.A. Compilation of Air Pollution Emission Factors, AP-42
Residual discharge information data base, Environment Canada, (Dec./90)

For the purposes of this analysis we consider any particulates recovered to be classified as ash. The available data on both industrial wood burning particulate emissions and present particulate abatement levels remains sketchy due to lack of consensus about these data. It is estimated that particulate recovery in the softwood lumber and plywood industry is in the order of 80% of the unabated particulate discharge, while relatively newer product plants have particulate recovery levels in the order of 95% (e.g. PSL, LVL and OSB plants).

3.2.2 Wood Ash

Anderson and Tillman (1977) estimate that 1.1% (by weight) of all wood waste burned becomes boiler ash. This ash is primarily comprised of calcium, sodium, magnesium and potassium and does not pose a large environmental threat when disposed of in landfills. Ash can be and is often used as a soil amendment fertilizer, which offers a less expensive as well as beneficial effect compared to disposing of ash in landfills. Accumulated ash via burning as well as particulate recovered has been included in solid waste totals throughout the report.

3.2.3 Water Demand

Another potential environmental concern during production of wood products is water usage and waste water discharge. The majority of the water used in production is in the form of steam energy for the drying of wood fibre. This steam is most often condensed and returned to be recycled or is off gassed as benign water vapour. Ponding of logs is often required to condition logs prior to initial breakdown (rotary peeling or waferizing in the case of plywood and OSB). These ponds are usually lined with a leaching barrier and the only water lost is through evaporation. No major effluent discharges result from structural wood product production destined for Canadian consumption.

3.2.4 Adhesive Use

A considerable and growing environmental concern surrounds the plastic resins used in the manufacture of wood products. Specifically, the concern is with off-gassing of formaldehyde from non-structural wood products containing urea formaldehyde (UF) glue within a finished structure. Formaldehyde emission rates from non-structural wood products are now regulated and have been reduced to levels of less than 0.25 ppm. The primary adhesive used in the production of structural wood building materials is phenol formaldehyde (PF). PF adhesives are waterproof and formaldehyde off-gassing is much lower than with UF glues (less than .2 ppm). In addition, use of vapour barriers in building construction effectively seal formaldehyde emissions away from inhabitants of the building. PF resin is synthesized from petroleum (phenol) and natural gas (formaldehyde) feedstocks. This feedstock energy represents about 60% of the total embodied energy of PF resin, but because it is not transformed via combustion it does not create any air emissions directly. Hence, the inclusion of feedstock energy in this analysis only reflects the additional draw down of our limited fossil fuel resources. Throughout this report, PF resins are assumed to be used by the "typical" plant for all products incorporating adhesives.

Other adhesives are being explored by the industry. Isocyanate resins are formaldehyde free and have garnered about 10% of the wood products adhesive market in North America. Isocyanates also use natural gas as a feedstock and is toxic until cured in the product; after which, it is stable and safe to users of the product. Lignin based adhesives have only recently come into production. Lignin itself is the natural adhesive that binds the cellulose of a tree together. It is derived from spent sulphite liquor produced during pulp production and uses renewable biomass rather than fossil fuels as its feedstock.

3.3 References

Anderson and Tillman 1977. Fuels from Waste. Academic Press, New York, N.Y.

4.0 FOREST HARVESTING, ROUNDWOOD TRANSPORT & FOREST MANAGEMENT

4.1 Introduction

This section focuses on the energy required to gain access, harvest and transport roundwood from the forest to the mill. It also includes the energy required to manage and sustain the forest growing stock into perpetuity, as the renewability of the forest resource is an important aspect and decision criterion in the choice and use of wood and its substitutes. Forest access refers to road construction and maintenance activities. Harvesting includes those activities between removing the tree from the stump to delivering it to roadside and transportation covers roadside to mill delivery of roundwood.

Both harvesting (stump to roadside) and roundwood transport (roadside to mill) are highly variable operations and are specific to each roundwood processor. All mills strive to maintain a constant delivered wood cost to their operations, which translates in part into a constant energy use. The actual wood cost level, however, is a function of the mill's conversion efficiency, product type and value, and prevailing market conditions for its product; all of which are subject to fluctuation. The energy used in harvesting can also vary significantly across mills producing a similar product with similar technology in the same region due to the interaction of a number of variables. Some of these variables pertinent to harvesting and wood transport include:

<u>Harvesting</u>

- manual or mechanized logging
- skidding distance
- forwarder type and capacity
- tree species, size, etc.
- terrain

<u>Transport</u>

- road quality
- vehicle type & capacity
- tree species, size, etc.
- haul distance

Such a large number of variables makes it impossible to estimate delivered wood energy use by product or region within a stipulated confidence interval. The inherent variability in harvesting and road transport is too great to achieve a realistic energy use profile. Instead, a single figure is used across all products and regions. Such a figure also suffers from regionalization bias, but it does not unduly misrepresent the perceived accuracy of providing regional estimates by product and may actually off-set or counter the pronounced range of values both within and between regions.

4.2 Direct Energy Use in Access, Harvest and Roundwood Delivery

Three different studies reporting harvesting and roundwood delivery figures serve as the primary sources for the energy use estimate. References for these three studies are provided at the end of this section. Two of the studies (CORRIM and ENFOR) are somewhat dated, while the Torrie & Smith study was completed in 1991. All three studies differ in their methodology, source data, and assumptions making it difficult to compare their results. The resulting estimates for harvesting and roundwood transport energy reported in the three studies are shown below:

Study-Year	Estimate Gj/o.d.t	Remarks
CORRIM-76'	0.602	U.S. study using industry data
ENFOR-80'	0.845	CAN. study using case studies and industry surveys
T&S - 91'	0.987	based on Stat. Can. data and industry estimates

Chronologically, the three studies indicate an increase in energy use. This increasing energy use over time may reflect greater mechanized logging and/or longer haul distances. While the three studies report energy use figures within a fairly narrow range, it was still necessary to formulate a level of confidence about the estimates by further inspection of their underlying assumptions, methodology and source data.

The CORRIM study results were judged to be inapplicable to Canadian industry for two reasons: (1) the haul distances in the U.S. are on average shorter than those faced by Canadian firms; and, (2) the denser public road network in the U.S. relative to Canada also skews energy use towards a lower estimate.

The ENFOR study provided the most detail of the three studies and besides containing a lengthy international literature review, it was also accompanied by Canadian industry surveys and engineering case studies.

The Torrie and Smith Associates report lacked detail and drew heavily on Statistics Canada data. Their resulting estimate was actually provided by the Canadian Pulp and Paper Association, which aggregated the transport of pulp chips and sawmill residues to pulp mills with roundwood harvesting and hauling. The inclusion of these less dense products (e.g. chips and residues) skewed the estimate toward a higher energy profile due to the smaller mass loads achieved with these bulky, less dense products. With pulp chips accounting for approximately 59% of the raw furnish input to pulp and paper operations across the country, the inclusion of chips and residues in the energy use figure becomes a significant factor.

Due to the limitations of the CORRIM and Torrie and Smith studies, the ENFOR estimate was selected for use in this study. A breakdown of their energy use estimate into access and harvesting and hauling is provided below:

Activity	Gj/o.d.t (diesel fuel equivalent)
access & harvest	0.434
hauling	0.411
Total	0.845

Notes: Access energy is relatively small (0.021 Gj/o.d.t) and has been included with harvest energy.
Hauling energy corresponds to 245 km round-trip @ 1.67 Mj of diesel fuel/ tonne-km.

As reported above, transportation energy accounts for close to 50% of the total energy used to deliver roundwood to the mill. The transportation energy factor of 1.67 Mj/tonne-km was provided by the ENFOR study, but can also fluctuate widely as it is a function of a number of site specific and vehicle type variables. However, this energy use factor is some 40% higher than that for usual diesel truck highway transport (1.18 Mj/tonne-km). The higher energy consumption is ascribed to longer idle times and greater travel distances on logging roads. The deduced round-trip travel distance is by no means a steadfast figure. Again, mills even within the same region can face considerably different haul distances. For instance, a recent study of 17 of Ontario's softwood sawmills indicates an average one-way haul of 135 km, but varying between as little as 60 km to as much as 300 km. Forintek studies of softwood sawmills in Quebec indicate an average one-way haul distance of 120 km, but again considerable variation was found. The ENFOR study noted that central Canada producing regions experienced longer haul distances than elsewhere in the country. While no published figures exist for average hauling distances, we are confident that our distance figure adequately reflects road transport of roundwood across the country.

4.3 Forest Management

The energy expended in forest renewal was taken from a report prepared by Weyerhauser company in the U.S.; one of the largest private forest stewards in the world. Weyerhauser estimates that it requires 0.232 Gj of energy per o.d. tonne of roundwood to sustain the renewability of the forest. One-third of this energy is electricity used in nursery operations with the remainder being diesel fuel used for site preparation and out-planting.

4.4 Energy Profile Summary

The average total energy used in the harvesting, transport and renewal of forest roundwood is calculated to be 1.077 Gj/o.d. tonne and is comprised of the following energy sources:

Energy Type	Harvesting	Activity Transportation	Management
		(Gj/o.d.tonne)	
diesel fuel	0.356	0.411	0.155
gasoline	0.078	-	-
electricity	-	-	.077

Typical energy use ranges for harvesting and transportation are reported in the ENFOR study and vary between a low of 0.653 and a high of 1.013 Gj/o.d. tonne. Manual logging is considerably less energy intensive (0.206 Gj/o.d.t) than mechanized harvesting systems (0.510 Gj/o.d.t). The figure used in this study favours the higher ENFOR estimates for harvesting and transportation.

4.5 Air Emissions Summary: Roundwood

	CO_2	**CO**	**CH_4**	**NO_x**	**SO_2**	**VOC**	**Partic.**
	Kg	.... grams					
Per O.D. tonne of Roundwood	70	705	23	769	95	114	-

Note: excludes purchased electricity emissions

The above chart depicts the direct energy related air emissions for roundwood extraction and delivery to the mill yard. These figures have been derived using the energy profile information in Section 4.4 and the air emission factors listed in Appendix A. At this writing, the research alliance had not adopted a complete set of emission factors for purchased electricity, and hence, these emission impacts have not been included. A number of other environmental impacts are associated with roundwood extraction and include such aspects as wildlife habitat disturbances, carbon cycling within the forest ecosystem, soil erosion and nutrient depletion to name but a few. These additional impacts on the environment are being analyzed in a related alliance study and will also be incorporated into the systems model once they become available.

4.6 References

Committee on Renewable Resources for Industrial Materials (CORRIM). J. Wood Sci. Tech. Vol. 8, No. 1 (1976).

Bingham, C.W. 1975. Keynote address. For. Prod. J. Vol. 25, No.9.

Ash, M.J., P.C. Knoblock and N. Peters. 1980. Energy Analysis of Energy from the Forest Options. ENFOR Project P-59.

Torrie Smith and Associates 1991. Energy use and requirements of Canadian forest products sector and implications for carbon modelling of the forest sector. Prepared in association with ESSA Environmental and Social Systems Ltd. for Forestry Canada.

W.B. Trusty and Associates Ltd. 1992. Ontario's spruce, pine, fir (SPF) sawmill industry: an economic update. Prepared for the Ontario Ministry of Industry, Trade and Technology.

5.0 KILN DRIED SOFTWOOD LUMBER

5.1 Introduction

Almost every province of the country produces softwood lumber in various amounts and sizes depending on their inherent forest wealth and size of trees. There are over 1100 sawmills in Canada producing softwood lumber. Four provinces account for 95% of all softwood lumber produced in the country (Table 2).

Table 2
SOFTWOOD LUMBER PRODUCTION AND RECOVERY FACTORS FOR MAJOR SOFTWOOD LUMBER PRODUCING REGIONS

Region	Annual Production Volume (MMBM)	Lumber Recovery (L.R.) %	Wt. Ave. L.R. by Volume %	Common Lumber Sizes Produced
Quebec	4750	51.9	10.02	2x3 to 2x8
Ontario	2520	48.4	4.98	2x3 to 2x8
BC int./Alta	13180	54.3	29.16	2x3 to 2x12
BC coast	4100	63.7	10.64	2x3 to 2x12
Total	24550		54.80	

Note: Reported figures are three year averages from 1988 to 1990. A country wide recovery figure of 54.0% has been used in this study unless otherwise stated.

Sources: Statistics Canada Cat. No. 35-204 (88-90).
Forintek Canada Corp. data files.

As set out in the research guidelines adopted by the research alliance, a generalized material balance and energy profile will be developed for kiln-dried softwood lumber produced across the country. All framing lumber (2x3 to 2x8) is assumed to be produced and sourced from within the province the building is located. All joist lumber (2x10 and larger) is assumed to come from the B.C. interior and/or Alberta irrespective of the location of the building. Transportation distances and associated environmental impacts will be developed accordingly. The information provided in Table 2 outlines the generalized basis for the proceeding estimates. A country wide weighted average lumber recovery figure (col. 4) has been derived using three year averaged annual production volumes as the weighting factor (col. 1) and regional recovery figures for the major producing regions (col. 2). The final column lists common lumber sizes produced in these regions of the country.

5.2 Product Yields

1 o.d.tonne of roundwood yields:

0.54 o.d.t of k.d. softwood lumber
0.25 o.d.t of pulp chips and shavings (co-products)
0.21 o.d.t of hogfuel/wood waste (bark and sawdust)

Sources: Corrim (1976) J. Wood. Sci. Tech. Vol. 8, No. 1.
Forintek Canada Corp. data files.
Statistics Canada (various annual catalogues).

Gross roundwood required per o.d.t of K.D. softwood lumber
= 1/0.54 = 1.852 o.d.t of roundwood

<u>Roundwood Energy Balance</u> (net of co-product production)
Roundwood delivered energy
= 1.852 o.d.t x 1.077 Gj/o.d.t x .75
= 1.496 Gj

5.3 Manufacturing Energy

Manufacturing energy in lumber production has been studied extensively around the world. Much of this work dates back to the oil crisis of the early 1970's. The table below summarizes a number of these estimates. The primary source for the estimates is Baird and Aun (1983). Other estimates have been inserted by Forintek.

Table 3
ENERGY COEFFICIENTS FOR FINISHED LUMBER

Source - YR	Country	Mj/kg
Chapman, P.F. - 68'	U.K.	6.4
Stein et al. - 67'	U.S.	4.3
Pick & Becker - 75'	U.S.	3.4
Hill, R.R. - 78'	Aust.	9.3
MacKillop - 67-69'	U.K.	0.4
Makhijani & Lichtenberg - 68'	U.S.	3.3
CORRIM - 76'	U.S.	2.8
Beca Carter et al. - 83'	N.Z.	5.3
Brown et al. - 85'	U.S.	4.4
CIPEC - 89'	CAN.	1.5
CMHC - 91'	CAN.	8.0
This Study	CAN.	5.8

Sources: Baird, G. and C.S. Aun 1983. Energy cost of houses and light construction buildings. New Zealand Energy Research and Development Committee. Rep. No. 76.

Additional sources compiled by Forintek and include:

Brown, H.L., B.B. Hamel and B.A. Hedman. 1985. Energy analysis of 108 industrial processes. Fairmount Press.
Canadian Industry Program for Energy Conservation (CIPEC) 1989. Taskforce report to Energy, Mines & Resources Can.
CMHC 1991. OPTIMIZE: a method for estimating the life cycle energy and environmental impact of a house. Consultants report to Canada Mortgage and Housing Corp.

As is evident the estimates vary over a wide range. Much of the differences in the estimates is due to source data and method/level of analysis. In preparing our estimate we reviewed all studies employing level II IFIAS system boundaries, which is the chosen level of detail for this project.

Energy demand differs considerably across mills due to the use of different combinations of log merchandisers, sawing equipment, optimizers, planing facilities and kiln types. Using a number of the above reported studies along with our own information, we have compiled the gross mechanical and process heat requirements for one O.D. tonne of lumber (Table 4). In practice, kiln-dried lumber is sold on a volumetric board foot basis with a moisture content of approximately 15%, and one O.D. tonne of softwood lumber equates to a volume of 1585 nominal board feet (Nielson et al. 1985).

Table 4
ENERGY REQUIREMENTS IN THE PRODUCTION OF KILN DRIED SOFTWOOD LUMBER

	Gross Mechanical Energy	Gross Process Heat
	(Gj per O.D. tonne of lumber)	
Lumber	0.251	3.918
Co-products	0.316	1.679
Hogfuel	0.151	-
Total	0.718	5.597

Mechanical energy represents about 13% of the total gross energy used. A generalized distribution of mechanical energy would be as follows: primary and secondary breakdown equipment use 25% of the energy; kiln fans and other ventilation use another 25%; 20% is used in miscellaneous support items such as lighting, controls and small machinery; and the remaining 30% is distributed in various proportions among conveyors, planers and sorting equipment. Thermal energy requirements are primarily a function of the percentage of lumber dried, the mill location, kiln efficiency, wood properties and its initial moisture content (MC). The process heat stipulated above is based on a drying schedule to achieve 15% MC or 19% MC on average.

5.4 Hogfuel Utilization / Net Solid Waste

Methods and source fuels for drying lumber vary considerably across the country. It is estimated that approximately 52% of the process heat energy used to dry lumber is generated from burning hogfuel produced on-site. The remainder of the required energy is derived primarily from fossil fuels (Gingras, 1983; CIPEC, 1989; Forintek data files). Hogfuel utilization is arrived at as follows:

- gross heat energy required to process one kg of lumber = 5.597 Mj
- 52% of the gross process energy (2.910 Mj) is derived from hogfuel
- the mill generates 0.389 o.d. kg or 0.778 green kg of hogfuel (@ 100% moisture content) per o.d. kg of lumber
- at a boiler efficiency of 65%, one green kg of hogfuel yields 5.72 kg of pressurized steam or 13.3 Mj (Marks, 1941; CORRIM, 1976; Nielson et al., 1985). Therefore, 0.778 green kg of hogfuel can yield 4.45 kg of steam or 10.35 Mj.

- hogfuel utilization is (2.91 Mj / 10.35 Mj) x 0.778 kg = 0.22 green kg or 0.11 kg o.d. of hogfuel per kg of lumber produced. As a percent of hogfuel produced, utilization is 28.3%

- the burning of 0.11 o.d. kg of hogfuel produces an additional 0.0012 kg of boiler ash (0.11 kg x 1.1% - see section 3.2.2)

- stack particulates recovered amounts to another 0.0016 kg (2.91 Mj x .7076 g/Mj x 0.8 - see section 3.2.1)

- therefore net solid waste produced = 0.282 o.d. kg / kg of lumber

therefore net solid waste produced	= 0.282 o.d. kg / kg of lumber
unused hogfuel	= 0.279 o.d. kg
ash accumulation	= 0.0012 o.d. kg
particulates recovered	= 0.0016 o.d. kg
	0.282

5.5 Material Balance and Energy Profile Summary

Resource Use / Solid Waste:

per o.d. tonne of finished product:

Gross input	= 1.852 tonnes
Net input	= 1.389 tonnes (net of coproduct contribution)

Net Solid Waste (kg) / tonne of finished product

unused hogfuel	= 279 kg
ash + particulate recovery	= 3 kg
total	282 kg

Net Energy Use: (exclusive of coproducts)

	Extraction	Manufacturing	Total
	(Gj per O.D. tonne of K.D. Lumber)		
Mechanical	0.107	0.402	0.509
Thermal	1.389	3.918	5.309
Total	1.496	4.320	**5.816**

Note: One thousand board feet (MBM) of K.D. lumber at 15% MC weighs 725 kg and one O.D. tonne of lumber weighs 1150 kg at 15% MC, which yields 1.586 MBM of lumber. (derived from Nielson et al., 1985). Therefore, total net energy per MBM of lumber = 3.667 Gj.

5.6 Air Emissions Summary: K.D. Softwood Lumber

Activity Stage/ o.d. tonne	**CO_2** Kg	**CO**	**CH_4**	**NO_x** .... grams	**SO_2**	**VOC**	**Partic**
Resource Extraction	98	979	32	1068	132	158	-
Manufacturing	419	83	33	559	119	81	407
TOTAL	517	1062	65	1627	251	239	407

Note: National process heat fuel use in manufacturing: N.gas, 39.8%; HFO, 4.1%; LPG, 4.1%, hogfuel, 52% (Stats Can. 57-208).

Excludes purchased electricity.

Excludes emissions for finished product to final market transportation.

5.7 Unit Factor Estimates: K.D. Softwood Lumber

A unit factor defines the resource inputs and environmental outputs associated with a unit of production. The unit factors listed below are those incurred during the extraction and manufacture of one thousand board feet (MBM) of kiln-dried softwood lumber, exclusive of electricity use effects.

Inputs: per MBM of K.D. softwood lumber

Materials: 876 o.d. kg of roundwood

Energy:
321 Mj of electricity
808 Mj of diesel fuel
68 Mj of gasoline
983 Mj of N.gas
1285 Mj of hogfuel
101 Mj of LPG
101 Mj of HFO

Outputs: per MBM of K.D. softwood lumber

Air: 326 kg of CO_2
670 g of CO
41 g of CH_4
1026 g of NO_x
158 g of SO_2
151 g of VOC
257 g of Particulates

Solid: 176 o.d. kg of bark/wood waste
1 o.d. kg of boiler ash
1 o.d. kg of recovered particulates

5.8 References

Marks, L.S. 1941. Mechanical Engineers Handbook. McGraw-Hill Book Co., New York, N.Y.

Gingras, J.F. 1983. Energy in the wood products industry. Unpublished manuscript updated by Forintek Canada Corp. 1991.

Nielson, R.W., Dobie J. & D.M. Wright 1985. Conversion factors for the forest products industry in western Canada (eastern Canada edition in review) Forintek Canada Corp. SP No. SP-24R.

6.0 SOFTWOOD PLYWOOD

6.1 Introduction

Softwood sheathing plywood production is concentrated in British Columbia with approximately 25 mills producing the product. For purposes of this study all mechanical energy used in the production of plywood sheathing will be assumed to come from the B.C. provincial electricity grid.

6.2 Product Yields

1 o.d.tonne of roundwood yields:

0.50 o.d.t of sheathing plywood
0.38 o.d.t of co-products (peeler core, chips and shavings)
0.12 o.d.t of hogfuel/wood waste (bark and sawdust)

Sources: Corrim (1976); Nielson et al. (1985).
Forintek Canada Corp. data files.
Forestry Canada 1991. Selected forestry statistics. Information Report E-X-46.

Gross roundwood required per O.D. tonne of sheathing plywood
= 1/0.5 = 2.0 O.D. tonnes of roundwood

Roundwood Energy Balance (net of co-product production)

Gross roundwood delivered energy
= 2.0 o.d.t x 1.077 Gj/o.d.t x .62
= 1.335 Gj

6.3 Manufacturing Energy

Peeling of logs is less energy intensive than sawing logs for lumber. Process heat use in the form of steam energy is much higher in plywood manufacture as it is used throughout the process from log conditioning to the eventual hot pressing of the plywood panels. The following heat distribution guidelines are generally valid, however, large seasonal variations do occur (Gingras, 1983):

Production Stage	% Process Heat Used
log conditioning	30
veneer drying	55
hot pressing	10
space heating	5

Table 5 shows the estimated mechanical and process energy figures for the manufacture of structural sheathing plywood. These figures are comparable to published results, however, different measurement units and levels of analysis used in other reports allow for only limited comparison (CORRIM, 1976; CMHC, 1991; Baird and Aun, 1983; Gingras, 1983; Malin, 1992).

Table 5
ENERGY REQUIREMENTS IN THE PRODUCTION OF SOFTWOOD STRUCTURAL SHEATHING PLYWOOD

	Gross Mechanical Energy	Gross Process Heat
	(Gj per O.D. tonne of Plywood)	
Plywood	0.167	7.211
Co-products	0.066	2.446
Hogfuel	0.118	-
Total	0.351	9.657

6.4 Hogfuel Utilization / Net Solid Waste

Process heat is derived from hogfuel produced by the mill and purchased natural gas. Approximately 50% of the gross process heat energy consumed by plywood manufacturers is derived from hogfuel (Gingras, 1983). The remainder of the required energy is derived from natural gas. Hogfuel utilization is approximately 76% or 0.18 kg of the 0.24 kg of hogfuel produced per kg of plywood. Accumulated boiler ash and particulate recovery nets an additional 0.005 kg of waste per kg of plywood. See Section 5.0 on softwood lumber for hogfuel use and solid waste produced calculation methodology.

6.5 Adhesive Energy

Phenolic resin (phenol formaldehyde) is the adhesive of choice for use in plywood production. The manufacture of phenolic resins is particularly energy intensive. The embodied energy is estimated to be 86.97 Mj/kg of resin (Franklin Associates, 1991), 60% of which is feedstock energy (see Appendix C). Adhesive use, as a percent of final product weight, is about 1.8 percent or 18 kg per O.D. tonne of plywood; representing an energy input of 1556 Mj.

6.6 Material Balance and Energy Profile Summary

Resource Use / Solid Waste:

per o.d. tonne of finished product:

Gross input	= 2.000 tonnes
Net input	= 1.240 tonnes (net of coproduct contribution)

Net Solid Waste (kg) / tonne of finished product

unused hogfuel	= 60 kg
ash + particulate recovery	= 5 kg
total	65 kg

Net Manufacturing Energy Use: (exclusive of coproducts)

	Extraction	Manufacturing	Total
	(Gj per O.D. tonne of Plywood)		
Mechanical	0.096	0.285	0.381
Thermal	1.239	7.211	8.450
Total	1.335	7.496	**8.831**

Net Adhesive Energy: 1.556 Gj / tonne of plywood

Total Net Energy: **10.397 Gj** / tonne of plywood

One thousand square feet (MSF) of softwood sheathing plywood (3/8" basis) weighs 335 kg and one O.D. tonne of plywood, as sold, weighs 1050 kg at 5% MC, which yields 3.134 MSF of plywood. (derived from Nielson et al., 1985). Therefore, total net energy per MSF of plywood = 3.317 Gj

6.7 Additional Process Related Emissions

One particular emission concern in the manufacture of plywood is the production of VOC's during the rapid drying of veneer. Within the wood are natural resins which are drawn out in tandem with the water vapour through exhaust vents. These vaporous resins are volatile organic compounds (turpenes and complex turpenes) and often can be visible to the eye as a blue haze. These VOC's can react with nitrogen oxide(s) to produce low level ozone. The industry has taken steps to reduce VOC discharges during veneer drying. As of 1990, VOC emissions at this stage of production was in the order of 0.742 kg/thousand square metres of product (0.0742 kg/MSF or 0.239 kg/tonne of product).

6.8 Air Emissions Summary: Plywood Sheathing

Activity Stage/ 1 o.d. tonne	**CO_2** Kg	**CO**	**CH_4**	**NO_x** .... grams	**SO_2**	**VOC**	**Partic.**
Resource Extraction	87	874	29	953	118	141	-
Manufacturing	500	112	35	668	30	408	699
TOTAL	587	986	64	1621	148	549	699

Note: Additional air emissions associated with adhesive use: 31 g phenol.

Manufacturing figures inclusive of energy, process and adhesive related emissions. Combustion energy adjusted to reflect softwood plywood manufacture in B.C.

Excludes purchased electricity emissions.

Excludes emissions for finished product to final market transportation.

6.9 Unit Factor Estimates: Plywood Sheathing

Inputs: per MSF (3/8" basis) of plywood

<u>Materials</u>: 385 o.d. kg of roundwood
5.4 o.d. kg of PF adhesive

<u>Energy</u>: 151 Mj of electricity
374 Mj of diesel fuel
31 Mj of gasoline
1271 Mj of N.gas
1115 Mj of hogfuel
298 Mj of feedstocks

Outputs: per MBF (3/8" basis) of plywood

Air:	187 kg of CO_2
	314 g of CO
	20 g of CH_4
	517 g of NO_x
	47 g of SO_2
	175 g of VOC
	223 g of Particulates
	10 g of phenol
Solid:	18.6 o.d. kg of bark/wood waste
	.6 o.d. kg of boiler ash
	.8 o.d. kg of recovered particulates

6.10 References

Franklin Associates 1991. Comparative energy evaluation of plastic products and their alternatives for the building and construction and transportation industries; final report. Prepared for The Society of the Plastics Industry, Inc.

Malin, N. 1992. Assessing sheathing options. Environmental Building News. Vol.1, No.2 September/October 1992.

Environment Canada. 1990. Residual discharge information system: emission factors.

7.0 ORIENTED STRAND BOARD (OSB) / WAFERBOARD (WB)

7.1 Introduction

A total of 14 OSB/WB mills have been established across Canada with eleven of these mills operating in 1992. These mills are located in each of the four regions considered in this study and thus, a generalized analysis has been prepared for the whole country.

7.2 Product Yields

1 o.d.tonne of roundwood yields:

0.69 o.d.t of sheathing OSB/WB
0.31 o.d.t of hogfuel/wood waste (wafer slivers, fines, bark and sawdust)

Sources: Neill, 1980; Nielson et al., 1985; CORRIM, 1976.
Forintek Canada Corp. data files.
Forestry Canada 1991. Selected forestry statistics. Information Report E-X-46.

Roundwood required per O.D. tonne of OSB/WB sheathing
= 1/0.69 = 1.45 O.D. tonnes of roundwood

Roundwood Energy Balance

Net roundwood delivered energy per o.d.t of OSB/WB
= 1.45 o.d.t x 1.077 Gj/o.d.t
= 1.562 Gj

7.3 Manufacturing Energy

OSB/WB panel production is similar to plywood production in the initial manufacturing steps prior to primary breakdown; i.e., logs are conditioned in a heated pond and debarked. Waferizing is considerably more energy intensive than peeling logs for veneer and more pressure is exerted during the pressing of OSB panels than plywood, which results in denser panel. The following energy values have been computed for 3/8" (9.0 mm) thick OSB/WB with a finished panel density of 40 lbs./cu.ft. (640 kg/cu.m) derived from aspen logs with a wood density of 24 lbs./cu.ft. (350 kg/cu.m). At these stated processing parameter levels, one O.D. tonne of OSB/WB is equivalent to 1.761 MSF of product at a thickness of 3/8" (9.0 mm) (Neilson et al., 1985). The below quoted figures compare favourably with other reported results (CORRIM, 1976; CMHC, 1991; Malin, 1992).

Table 6

ENERGY REQUIREMENTS IN THE PRODUCTION OF STRUCTURAL OSB/WB SHEATHING

	Gross Mechanical Energy	Gross Process Heat
	(Gj per O.D. tonne of OSB/WB)	
OSB/WB	0.815	4.158
Hogfuel	0.026	1.871
Total	0.841	6.029

Sources: Neill, 1980.
Forintek data files (Composites Dept.).

7.4 Hogfuel Utilization / Net Solid Waste

Process heat is derived from hogfuel produced by the mill and purchased natural gas. Approximately 80% of the gross process heat energy consumed by OSB/WB manufacturers is derived from hogfuel (Neill, 1980, Gingras, 1983). The remainder of the required energy is derived from natural gas and fuel oil. Taking into consideration proportional fuel type use and their burning efficiencies, hogfuel utilization is approximately 40% or 0.181 kg of the 0.450 kg of hogfuel produced per kg of OSB/WB, which results in .269 kg of unused hogfuel per kg of finished product. In addition, recovered boiler ash and flue particulates account for an additional .005 kg of solid waste per kg of OSB/WB (refer to section 5.0 for details concerning hogfuel use and solid waste calculation methodology.

7.5 Adhesive Energy

Phenolic resin (phenol formaldehyde) is also the adhesive of choice for use in OSB/WB production in Canada. However, adhesive use is a little more intensive in OSB/WB production as in plywood production averaging about 2% by weight (Forintek data files, Composites Dept.). The embodied energy of the phenolic resin used is approximately 1740 Mj/tonne of OSB/WB (see Appendix C).

7.6 Material Balance and Energy Profile Summary

Resource Use / Solid Waste:

per o.d. tonne of finished product:
Net input = 1.450 tonnes

Net Solid Waste (kg) / tonne of finished product
unused hogfuel = 269 kg
ash + particulate recovery = 5 kg
total 274 kg

Net Manufacturing Energy Use: (exclusive of coproducts)

	Extraction	Manufacturing	Total
		(Gj per O.D. tonne of OSB/WB)	
Mechanical	0.112	0.841	0.953
Thermal	1.450	6.029	7.479
Total	1.562	6.870	**8.432**

Net Adhesive Energy: 1.740 Gj / tonne of OSB/WB

Total Net Energy: **10.172 Gj** / tonne of OSB/WB

Note: One thousand square feet (MSF) of OSB/WB sheathing (3/8" basis) weighs 590 kg and one O.D. tonne of plywood,as sold, weighs 1040 kg at 4% MC, which yields 1.761 MSF of OSB/WB. (derived from Neilson et al., 1985). Therefore, total net energy per MSF of OSB/WB = 5.776 Gj.

7.7 Air Emissions Summary: OSB Sheathing

Activity Stage/ o.d. tonne	**CO_2**	**CO**	**CH_4**	**NO_x**	**SO_2**	**VOC**	**Partic.**
	Kg	.... grams					
Resource Extraction	102	1022	33	1115	138	165	-
Manufacturing	488	91	43	685	159	230	502
TOTAL	590	1113	76	1800	297	395	502

Note: Additional air emissions associated with adhesive use: 35 g phenol.
Manufacturing combustion energy source fuels: 80%, hog fuel; 17%, N.gas; 3% HFO.
Manufacturing figures inclusive of energy, process and adhesive relative emissions.
Figures exclude purchased electricity emissions.
Figures exclude emissions for finished product to final market transportation.

7.8 Unit Factor Estimates: OSB/WB Sheathing

Inputs: per MSF (3/8" basis) of OSB/WB

Materials:
823 o.d. kg of roundwood
11 o.d. kg of PF adhesive

Energy:
597 Mj of electricity
776 Mj of diesel fuel
64 Mj of gasoline
878 Mj of N.gas
119 Mj of HFO
2739 Mj of hogfuel
571 Mj of feedstock energy

Outputs: per MBF (3/8" basis) of OSB/WB

Air:
335 kg of CO_2
632 g of CO
43 g of CH_4
1022 g of NO_x
169 g of SO_2
224 g of VOC
285 g of Particulates
20 g of phenol

Solid:
153 kg of bark/wood waste
1 kg of boiler ash
2 kg of recovered particulates

7.9 References

Neill, R.D. 1980. Energy self-sufficiency for waferboard plants. Presented at the Canadian Waferboard Symposium. Toronto, Ontario.

8.0 ENGINEERED WOOD PRODUCTS

8.1 Introduction

Engineered wood products are just that: products for which loading tolerances are uniquely specified for defined applications. For the purposes of this project the following products comprise the engineered wood products category:

- Parallel Strand Lumber (PSL);
- Glulam Timbers and Beams;
- Light Frame Parallel and Pitched Chord Trusses.
- Laminated Veneer Lumber (LVL);
- Prefabricated wood I-joists; and,

While some of these products are relatively new they all have applications in the light commercial construction sector. The material and energy profiles for these products were developed in close consultation with equipment and product manufacturers, which include:

- MacMillan Bloedel
- Tembec, Temlam Division
- Gang-Nail Canada Inc.
- Durante Raute
- Western Archrib
- Trus Joist MacMillan

8.2 Product Descriptions

Parallel strand lumber and laminated veneer lumber are commonly referred to as composite lumber products. These products have a promising future and offer larger sizes of lumber from smaller, lower grade logs as well as, a consistent quality and loading uniformity. LVL is processed in a manner similar to plywood but consists only of parallel laminations. Using various technologies the veneers are rotary peeled, dried, graded, spread with adhesive, laid-up into the desired depth and then pressed and cut to the desired width and length. In Canada, there is only one LVL mill operating in the province of Quebec. PSL is made from long strands of wood which is extruded with resin into various cross-sections and lengths. PSL is also only produced at one mill located in the province of B.C.

Glue-laminated (GLULAM) timber beams and columns are a structural wood product assembled by bonding lumber parallel to the grain with an adhesive. GLULAM is the oldest example of built-up members using predetermined arrangements of various grades of small dimensional lumber to produce larger and better grade wood columns and beams. GLULAM production is concentrated in western Canada (3 firms in B.C.and one each in Alberta and Manitoba). In eastern Canada there are two GLULAM production plants; one in Quebec and the other in Nova Scotia.

Prefabricated wood I-joists are built-up members that are manufactured using sawn lumber or LVL flanges and structural panel (plywood/OSB) webs. The flanges and webs are bonded together using phenol formaldehyde adhesive, forming an "I" cross-sectional shape. While used primarily for floor and roof joists, I-joists have also been used as support beams, garage door headers and framing components. There are three plants across Canada producing various combinations and permutations of wood I-joists -two in Alberta and one in Quebec.

Two additional built-up members use a combination of wood products and steel fasteners or webbing to construct a structural building product. The first of these is a light frame truss, which combines lumber and steel fastener nailing plates in the design and manufacture of parallel chord floor and roof trusses and pitched chord roof trusses. These two products are designed for specific load applications. Typically, a parallel chord truss is specified on a depth basis, while pitched chord roof trusses are specified on the basis of total span and the desired pitch. The total number of light frame truss fabricators is estimated to be in the order of 300 firms across the country. They are all located within close proximity to urban areas, including the five market areas considered in the model.

The last product considered under this product segment is the steel open-web/wood chord joist. This product is often used in floor and roof joist applications and is fabricated using either sawn or LVL lumber and hollow steel tubing and pins to fasten the wood and steel webbing together. Currently, there are but two manufacturers of this product in Canada; one in Alberta and the other in Ontario.

8.3 Material Balance & Energy Profile Summary

Due to the proprietary nature of a number of these products and in some instances the small number of firms producing a given product, it is not possible to divulge material and energy profiles for individual products. Further, confidentiality will be maintained in the computer model by aggregating the above products under the engineered wood products category (the user must specify two or more engineered wood products to receive an aggregated results summary). Table 7 provides an indication of engineered wood product's material and energy use ranges and an average figure for discernable production aspects of the products.

Tables 8, 9 10 and 11 provide individual component material inputs, specifications and production factors for the three composite engineered wood products to be considered in the model. For each of the three composite products reverse engineering product analysis was used to derive the input factors for the various product types by depths and/or span. These component inputs along with the assembly production factors are then used to discern and compile the environmental impacts of the final product.

Table 8 provides a breakdown of primary products comprising the three wood "I" joist types that will be considered by the model. The variation in the depth of joist across all three joist types ranges from 9.5" to 30.0".

Table 9 describes the finished product specifications for three typical light frame truss types used in defined applications at predetermined loadings. Appendix D provides additional material profiles for the three product types over depths and spans as well as supporting information for arriving at the production factors listed in the table.

Product specifications and component material quantity estimates for the open web type joists are described in Tables 10 and 11.

Table 7
MATERIAL AND ENERGY BALANCE PROFILES FOR ENGINEERED WOOD PRODUCTS

	Average	Range
	(per O.D. tonne of Product)	
Materials:		
Resource use (net t)	1.5	1.2-1.7
net resource energy (Gj)	1.6	1.3-2.0
hogfuel utilization (%)	33	3-60
net solid waste (kg)	25	10-120
Adhesive use (kg)	25	0-55
adhesive energy (Gj)	2.2	1.0-4.8
Manufacturing Energy:		
Primary Manufacturing		
Mechanical (Gj)	3.0	0.9-3.0
Thermal (Gj)	7.0	0-7.2
Secondary Manufacturing		
Mechanical (Gj)	0.01	0.0-0.3
Thermal (Gj)	0.75	0.0-2.0
Secondary Transportation	0.26	0.0-0.7

8.4 Air Emissions Summary: Engineered Wood Products

Total Air Emissions/O.D. tonne of Product[1]

Product	**CO_2**	**CO**	**CH_4**	**NO_x**	**SO_2**	**VOC**	**Partic.**
	Kg	.... grams				....	
Glulam[2]	657	1390	82	2216	41	316	506
PSL[3]	750	1379	126	2291	25	660	371
LVL[3]	656	1063	107	1867	20	564	291
Light Frame Trusses							
- parallel chord[4]	879	4262	89	1775	10	449	431
Wood I-Joists[5]							
plywood web	736	1129	188	3528	31	652	566
OSB web	699	1282	145	2973	37	521	492
Open Web[6]	1015	1751	82	2211	209	1274	789

Notes:

[1] Reported figures exclusive of purchased electricity emissions, finished product transportation to final market destination. Inclusive of resource extraction, 1° and 2° combustion manufacturing emissions, adhesive emissions, process related emissions (where applicable), steel input emissions (where applicable) and transport of primary components to assembly plant emissions (where applicable).

[2] Additional fugitive emissions of 19.5 g phenol.

[3] Additional fugitive emissions of phenol 95 g for PSL and 85 g for LVL.

[4] Emissions calculated for 26" deep floor joist; see Table 9 for product description.

[5] Wood "I" figures calculated for 20" depth of joist using either plywood or OSB as webbing and LVL for flanges (see Table 8 for complete product description). In additional fugitive emissions of phenol 59 g (61 g) plywood webbing (OSB webbing).

[6] Emissions calculated for 24" depth of joist; see Table 10 for Truss Design #3, product description.

Table 8
PRIMARY PRODUCT USE FACTORS FOR WOOD "I"-JOISTS

Product Component Description (Spec No. I-25):

Flange: LVL 1.75" wide x 1.5" thick
Webbing: 0.375" thick plywood or OSB

I-25 Component Use Factors
(kg/lin.ft.)

	Depth of Joist (in.)	
	9.5	12.0
Web: plywood	.265	.355
OSB	.467	.590
Flange: LVL	.191	.191

Product Component Description (Spec No. I-35):

Flange: LVL 2.3" wide x 1.5" thick
Webbing: 0.375" thick plywood or OSB

I-35 Component Use Factors
(kg/lin.ft.)

		Depth of Joist (in.)			
	12.0	14.0	16.0	18.0	20.0
Web: plywood	.335	.391	.446	.502	.558
OSB	.590	.688	.787	.885	.984
Flange: LVL	.382	.382	.382	.382	.382

Product Component Description (Spec No. I-45):

Flange: MSR 3.5" wide x 1.5" thick
Webbing: 0.5" thick plywood or OSB

I-45 Component Use Factors
(kg/lin.ft.)

		Depth of Joist (in.)			
	14.0	16.0	18.0	20.0	22.0
Web: plywood	.521	.595	.669	.744	.818
OSB	.915	1.045	1.177	1.309	1.440
Flange: MSR	.967	.967	.967	.967	.967

		Depth of Joist (in.)		
	24.0	26.0	28.0	30.0
Web: plywood	.892	.966	1.042	1.114
OSB	1.571	1.702	1.833	1.964
Flange: MSR	.967	.967	.967	.967

Source: Neilson et al. 1985. Conversion factors for the forest products industry in Western Canada. Forintek No. SP-24R.

Table 9

MATERIAL BALANCE AND ASSEMBLY ENERGY PROFILES FOR TYPICAL PARALLEL AND PITCHED CHORD LIGHT FRAME TRUSSES

Product Specifications:

Parallel Chord Roof Truss
- bottom hung joist design, working load of 55 psf
- length/height ratio 20:1, adjacent truss spacing at 24"
- 16 & 20 gauge galvanized steel plates (density = 7850 kg/m^3)
- lumber use inclusive of strongbacks
- depth of truss 24.0"
- lumber in finished product = 2.31 bd.ft (1.67 kg)/lin.ft.
- Net steel plate in finished product = 0.12 kg/lin.ft.

Parallel Chord Floor Truss
- bottom hung joist design, working load of 85 psf
- length/height ratio 20:1, adjacent truss spacing at 16"
- 16 & 20 gauge galvanized steel plates (density = 7850 kg/m^3)
- lumber use inclusive of strongbacks
- depth of truss 24.0"
- lumber in finished product = 2.30 bd.ft (1.67 kg)/lin.ft.
- Net steel plate in finished product = 0.11 kg/lin.ft.

Pitched Chord Roof Truss
- peaked Howe design for commercial roof, working load 65 psf
- slope 3:12, adjacent truss spacing 24"
- 16 & 20 gauge galvanized steel plates (density = 7850 kg/m^3)
- lumber use inclusive of bracing
- span of truss 42.0 ft.
- lumber in finished product = 96 bd.ft (15.65 kg)
- Net steel plate in finished product = 3.51 kg

Production Factors
- purchased lumber utilization = 85%
- co-product production = 10% (e.g.- survey stakes, cross-bracing members, raw furnish to particle board mills, hogfuel for space heat, sold as firewood)
- net wood waste = 5%
- transportation distance for lumber from mill to truss fabricator = 337 km (road)
- truss fabrication energy = 0.7 Mj / truss (electricity)

Table 10

PRODUCT SPECIFICATIONS FOR TYPICAL OPEN WEB TYPE JOISTS

Product Specifications:

Open Web Truss No. 1
Top and Bottom Chords: 1.5" x 3.5" MSR Lumber
Webbing: steel tubing 1.0"-1.125" in diameter (various gauges)
Connectors: steel pins 0.375" in diameter
Min. Depth: 14" Max. Depth: 50"

Open Web Truss No. 2
Top and Bottom Chords: 1.5" x 3.5" LVL
Webbing: steel tubing 1.0"-1.125" in diameter (various gauges)
Connectors: steel pins 0.375" in diameter
Min. Depth: 14" Max. Depth: 50"

Open Web Truss No. 3
Top and Bottom Chords: Double 1.5" x 5.5" MSR Lumber
Webbing: steel tubing up to 2.0" in diameter (various gauges)
Connectors: steel pins 0.625"-1.25" in diameter
Min. Depth: 24" Max. Depth: 72"

Open Web Truss No. 4
Top and Bottom Chords: Double 1.5" x 3.5" MSR Lumber
Webbing: steel tubing up to 2.0" in diameter (various gauges)
Connectors: steel pins 0.625"-1.0" in diameter
Min. Depth: 20" Max. Depth: 60"

Open Web Truss No. 5
Top and Bottom Chords: Double 1.5" x 1.9" LVL
Webbing: steel tubing up to 1.0"-1.5" in diameter (var.gauges)
Connectors: steel pins 0.5"-0.75" in diameter
Min. Depth: 16" Max. Depth: 64"

Assembly Plant (Secondary) Energy Profile

Mechanical (electricity) = confidential
Natural Gas (process heat) = confidential

Solid waste: LVL and MSR lumber - 3% by weight
Steel - 0%

Source: Product specifications derived from Trus Joist MacMillan product catalogue
Assembly Energy estimates developed with E. Cattoi, Trus Joist MacMillan, Claresholm, Alberta

Table 11

MATERIAL QUANTITY ESTIMATES FOR SELECTED OPEN WEB JOISTS

Joist ID	Joist Depth (in.)	Total Joist Wt./L.F. (kg)	Wood Wt. /L.F. (kg)	Steel Wt. /L.F. (kg)
No.1	14.0	1.702	MSR 1.044	0.658
	50.0	1.928	MSR 1.044	0.884
No.2	16.0	1.770	LVL 1.134	0.636
No.3	24.0	4.401	MSR 3.221	1.180
No.4	20.0	3.403	MSR 2.087	1.316
No.5	16.0	2.064	LVL 1.497	0.567
	64.0	2.518	LVL 1.497	1.021

Source: D. Rice, Truss Joist MacMillan, Surrey, B.C.

Note: The above figures reflect domestic sources of LVL, MSR lumber and steel inputs.

APPENDIX A

AIR EMISSION FACTORS

	g/Mj						
	CO_2	CO	CH_4	NO_x	SO_2	VOC	Part.
Transportation:							
Gasoline	68.0	3.805	.043	.321	.014	.434	-
Diesel							
Road	70.7	.443	.022	.807	.102	.087	-
Rail	70.7	.057	.088	1.400	.102	.070	-
Marine	70.7	.180	.045	.240	.102	.390	-
HFO-Marine	74.0	.007	.040	.200	.102	.360	-
Thermal Combustion:							
Natural Gas	49.7	.015	.001	.059	.0002	.001	.048
LPG	59.8	.001	.001	.059	.0002	.001	.034
Wood/Bark	81.5	.011	.008	.110	.0002	.039	.708
HFO-Boiler	74.0	.014	.003	.160	.725	.003	.240

Sources: Emission Factors for Greenhouse Gases and Other Gases by Fuel Type: an inventory Ad Hoc Committee on Emission Factors, EMR, December 1990.

Particulate Estimates derived from ENV.CAN. Residual discharge information system: Emission Factors, Dec/90.

N.gas SCC 10200692; LPG SCC 10201002; HFO SCC 10200503; hog fuel SCC 10200906.

APPENDIX B

TRANSPORTATION FACTORS FOR STRUCTURAL WOOD PRODUCTS

Plywood & Large Dimension Lumber from Prince George, BC, to:

	Rail	Road (Kilometers km)	**Total**
Calgary	1148	25	1173
Winnipeg	2538	25	2563
Toronto	3980	25	4005
Montreal	4784	25	4809
Halifax	5745	25	5770

Note: Plywood used in Vancouver is produced within the city limites with an average road travel distance of 55 km

Wood “I” and Open Web Steel joists from Calgary, Alta to:

Vancouver	1049	25	1074
Winnipeg	1358	25	1383

Wood “I”-joists from Montreal, Que to:

Toronto	805	25	830
Halifax	962	45	987
Montreal	---	45	45

LVL from Villemarie, Que to:

Montreal	755	123	878
Toronto	1299	123	1422
Winnipeg	3149	123	3272
Halifax	2087	123	2210

LVL from Oregon to:

Calgary	1550	25	1575
Vancouver	700	25	725

	Rail	Road (Kilometers km)	**Total**
PSL from Vancouver, BC to:			
Calgary	1049	25	1074
Winnipeg	2455	25	2480
Toronto	4537	25	4562
Montreal	5340	25	5365
Halifax	6301	25	6326
Open web steel joists from Toronto, Ont to:			
Toronto	---	60	60
Montreal	805	25	830
Halifax	1765	25	1790

Within province transportation distances for narrow dimension softwood lumber and OSB are estimated at 337 km (by truck), except for Nova Scotia, where it is 65 km for lumber and 195 km for OSB.

Glulam used in Vancouver sourced locally (55 km); Glulam used in Calgary and Adhesive sourced in Alberta at distances of 300 km by road, and 1308 km by rail and 25 km by road; Glulam used in Toronto (803 km by rail and 25 km by road) and Montreal (30 km by road) sourced in Quebec; Glulam used in Halifax sourced locally at 30 km by road.

Transportation energy for delivering primary products to secondary assembly plants is estimated at 0.49 Mj/tonne-km for rail transport and 1.18 Mj/tonne-km for road travel.

Sources: Personal Correspondence, T. Liziak. Canadian National Railway, February, 1993. 1-800-361-9006.

Rand McNally Road Atlas (1984).

CMHC 1991. Optimize: a method for estimating the lifecycle energy and environmental impact of a house (Appendices).

Franklin Associates, Ltd., 1991. Comparative energy evaluation of plastic products and their alternatives for the building and construction and transportation industries. Final Report. Prepared for The Society of the Plastics Industry, Inc.

APPENDIX C

EMBODIED ENERGY AND PROCESS RELATED EMISSIONS DATA IN THE MANUFACTURE OF ONE TONNE OF PHENOLIC RESIN

Embodied Energy of Feedstocks	**Gj/tonne**
Natural Gas	20.5
Petroleum	31.4
Sub-total	51.9
Process Energy	
Heavy Oil	1.45
Gasoline	0.01
Natural Gas	26.90
Electricity	5.10
Sub-total	33.56
Transportation Energy	
(includes raw material & final product delivery to end-user)	
Diesel	
Road	1.17
Rail	0.34
Sub-total	1.51
Grand Total	**86.97**

Process Related Air Emissions

(exclusive of energy related emissions)

Fugitive and process related emissions for phenol formaldehyde production inclusive of intermediaries (phenol and formaldehyde) are provided in the figure below. These emissions are primarily fugitive process inputs (e.g. formaldehyde and phenol) as well as additional volatile organic compounds (VOC).

EMISSION FACTOR ESTIMATES FOR PHENOL FORMALDEHYDE PRODUCTION (inclusive of intermediaries)

1. Formaldehyde Production (silver catalyst method)

Source	**Pollutant**	**Emission (kg/tonne)**	**Control Devise**
Start-up vent	formaldehyde	0.10	-
storage	"	0.003	vent scrubber
handling	"	0.0004	vapour recovery unit
absorber	"	0.076	flaring
fractionator	"	0.017	-
		0.1964	

2. Phenol Production (cumene)

Source	**Pollutant**	**Emission (kg/tonne)**	
General Process	phenol	3.987	
storage	phenol	0.067	engineering estimates
fugitive	phenol	0.918	
		4.972	
oxidizer	benzene	0.002	
condenser	cumene	0.017	

3. Phenol Formaldehude Resin (65% formaldehyde/35% phenol)

Source	**Pollutant**	**Emission (kg/tonne)**
Process	formaldehyde	0.825
Storage	"	0.115
Fugitive	"	0.250
		1.19

SUMMARY

Production Source	Pollutant	Gross Emission (kg/t)	Formulation Use Factor	Net Emission (kg/t)
Formaldehyde	Formaldehyde	0.1964	.65	0.1277
Phenol	Phenol	4.972	.35	1.7402
Phenol	Benzene	0.002	.35	0.0007
Phenol	Cumene	0.017	.35	0.006
PF resin	Formaldehyde	1.190	1.0	1.19

TOTAL VOC (formaldehyde, benzene, cumene) = 1.3244 kg/tonne of PF resin
plus 1.74 Kg of phenol

Total emissions (manufacturing, process and transportation) are reported below.

Air Emissions[1]: Phenol Formaldehyde Adhesive

Emission Source per tonne:	**CO_2**	**CO**	**CH_4**	**NO_x**	**SO_2**	**VOC**	**Particulates**
	Kg	.... grams					
Manufacturing Energy							
HFO	107	20	4	232	1051	4	348
Gasoline	1	38	_1	3	_1	4	-
N. gas	1337	403	27	1587	54	27	1291
Electricity	-	-	-	-	-	-	-
Process Related[2]						1324	
Transportation Energy[3]	82	518	26	944	119	102	-
	24	19	30	476	35	24	
	1551	998	87	3,242	1259	19,511	1639

Notes

[1] Exclusive of electricity emissions

[2] In addition to the VOC emissions, phenol air borne derivatives are also released to the air in the amount of 1.74kg/tonne of resin.

[3] Transportation energy includes delivery of raw materials to the plant as well as delivery of PF resin to end users.

Sources:

TOXIC AIR POLLUTANT EMISSION FACTORS: a compilation for selected air toxic compounds and sources U.S. EPA-450/2-88-006a

Locating and Estimating Air Emissions from Sources of formaldehyde
U.S. EPA-450/4-84-007e

Franklin Associates, Ltd. 1991. Comparative energy evaluation of plastic products and their alternatives for the building and construction and transportation industries. Final Report. Prepared for The Society of the Plastics Industry, Inc.

Environment Canada 1990. Residual discharge information system; emission factors.

U.S.E.P.A. 1990. Toxic chemical release inventory data base